SOIL EROSION
AND PHOSPHORUS IN RUNOFF
FROM AGRICULTURAL CROPLAND
IN SOUTHWESTERN ONTARIO

A review of relevant literature

prepared for

ECOLOGICAL SERVICES FOR PLANNING LTD.

by

THE CENTRE FOR SOIL AND WATER CONSERVATION

University of Guelph

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1.0 INTRODUCTION

Soil and water conservation has, in recent years, received increased attention in Canada's scientific, political and academic forums. Recognition of the significance of non-point sources of pollution has resulted in a renewed commitment to understand and combat problem conditions. While a wide variety of possible non-point sources exist in Ontario, PLUARG studies (PLUARG 1978) indicated that two thirds of diffuse source phosphorus, found in Lake Erie, is directly related to agricultural activity.

The Southwestern Ontario Soil and Water Environmental Enhancement Program (SWEEP) has been developed to respond to existing and potential deterioration of soil and water resources. This co-operative federal-provincial initiative has as its goals 1) The reduction of phosphorus loading to Lake Erie by 200 tons per year by 1990, from non-point agricultural cropland sources and 2) the increased productivity of the primary agricultural sector in southwestern Ontario by reducing or arresting soil erosion and degradation.

Included in the SWEEP mandate is the evaluation of existing methods and development of new technologies which may be effective in addressing soil erosion and/or phosphorus loading problems. This report will attempt to facilitate this process by reviewing our current understanding of these problems as well as our ability to prescribe and implement solutions. Soil erosion and phosphorus loading will be examined with regard to physical processes, extent and distribution, perceived impacts and available remedies. In addition to documenting current knowledge and methods, informational deficiencies, which may impede the successful development of remedial measures, will be identified. It is hoped that identifying key issues and information gaps will help define research priorities and ensure that the financial and human resources of SWEEP are focused on areas of greatest need and potential. The desired end result of the research program will be the development and validation of technologies that are not only effective, but also acceptable to land managers in both their cost and complexity.

Although the soil erosion and phosphorus loading components of the program are closely related, they are examined separately in this report. The linkages and interdependencies that exist will be identified whenever appropriate. Despite the separation of possible solutions in this report it

is understood that high priority must be given to technologies which are thought to be effective against both soil loss and phosphorus yield.

2.0 SOIL EROSION

Soil erosion has been recognized, for many years, as a problem with potentially serious economic and environmental consequences. Excessive rates of soil loss threaten both the quality of Ontario's water resources and the economic viability of many of the farming enterprises. While there is presently renewed commitment to combat soil degradation, understanding of the problem is complicated by the many physical and human processes and interdependencies which are at work on the landscape. The major forms of soil degradation in Ontario are erosion and compaction. The most serious of these is soil erosion.

Increased soil erosion in Ontario is generally attributed to an increase in row crop production and a reduction in cereal grain and hay crop production (Miller 1984). Traditional mixed farming has now been replaced by specialization and the frequent separation of livestock and crop production. During the decade 1974 to 1984 the number of cattle in the Province of Ontario declined by over 20% (Ontario Ministry of Agriculture and Food 1986). This has resulted in lessened demand for hay crops and thus contributed to the proliferation of row cropping.

In order to ensure that new technologies will be effective in the field, their development must be based on a thorough understanding of all aspects of the soil erosion problem. Required background includes information on the physical processes, the causes and the impacts of erosion. In addition, we must be able to determine the extent and distribution of erosion, at large or small scale, in order to apply technologies to areas of greatest need.

2.1 Measurement and Prediction

To identify the existence of current or future agricultural productivity problems because of sheet or rill erosion, we must possess reliable techniques for both measurement and prediction. Measurement techniques provide detailed and reliable data on soil loss but require hands-on field level involvement. While such labour intensive methods are feasible in plot-sized examinations, their application to broadscale situations is generally thought to be cost prohibitive. Predictive methods

form the basis for regional analysis of soil loss and are required for the effective allocation of remedial measures.

As noted above, direct measurement of soil erosion is possible and has occurred in Ontario and elsewhere. Techniques include the long-term monitoring of field plots, the use of simulations and the use of tracers. Despite the apparent reliability of actual field measurement, Begg (1982) notes the necessity for long-term monitoring to ensure the validity of data.

Measurement of soil loss under simulated wind and rainfall conditions has been possible for many years. Apparatus such as wind tunnels, rainfall simulators and soil erosion flumes facilitate laboratory measurements of erosion, or more specifically, erodibility. Dickinson and Pall (1982) have utilized laboratory simulation to establish the seasonal variation of erodibility on several soil types from two southern Ontario watersheds. Measured values of erodibility are used as information inputs to predictive procedures which will be discussed later.

Tracers provide an effective method of measuring soil loss and are available in many forms (Carson and Kirby 1972). One currently evolving technology is the use of ^{137}Cesium as a tracer in the measurement of soil movement. This radioactive isotope was released in the atmosphere during the 1950's and 1960's. It has subsequently been removed from the atmosphere by precipitation and deposited worldwide. Ritchie, Spraberry and McHenry (1974) have established the validity of ^{137}Cesium as a tracer and concluded that it is possible to correlate measured movement of such radioactive material with soil loss. Studies are currently underway in Southern Ontario which are using ^{137}Cesium as a soil erosion measurement technique.

A study being conducted in Brant County, by Kachanoski and co-workers from the University of Guelph, is utilizing ^{137}Cesium as a method of measuring past erosion. Core samples taken 16 years ago have recently been tested for ^{137}Cs content. The analysis of current samples taken from the same sites will provide a valuable comparison from which soil loss can be calculated. Such studies provide not only opportunities to develop a data base of measured erosion, but also provide methods of testing and validating predictive techniques.

As noted above, the development of a data base of actual measured erosion on various landforms and soils is desirable. A review of relevant literature reveals that such information is very limited in Ontario. While

several studies have been conducted using various methodologies to estimate erosion and sediment problems only one has included detailed field checking of an area (Miller 1984). In-field measurement of soil loss and associated yield reduction comprised part of a 1982-1983 study conducted by Battiston and Miller (1984). This research focussed on a 300 km^2 area in Wellington County and the Region of Waterloo and examined the extent and severity of erosion and its effect on soil productivity.

The extent of erosion was measured through the use of aerial photography and findings were validated by field checking. The examination of stereo pairs enabled researchers to identify erosional phases within fields and over larger areas. Extrapolation enabled mapping of the study area and a means by which eroded areas were expressed as a percentage of total area. It was found that 18% of agricultural cropland in the study area was moderately to severely eroded. This study concluded that remote sensing techniques provide an accurate and fast method of delineating currently eroded areas at both large and small scale. It was also noted by Battiston and Miller (1984) that severe erosion typically occurred in small areas and in close proximity to less eroded sites. Eroded areas were most often associated with upper slope positions on knolls. These findings are of particular relevance to a discussion of remedial measures presented later in this report.

From the material reviewed, it is evident that satisfactory techniques for the measurement of soil loss are in existence. The data base of measured erosion on various Ontario soils is very limited, however, and more studies, using various measurement techniques, are needed. While such studies provide insights into the extent and distribution of past erosion, the analysis of potential erosion on broadscale levels requires methods for prediction.

Predictive tools used in the examination of both the amount and extent of soil erosion are based primarily on the Universal Soil Loss Equation. This equation, developed in the United States over two decades ago, has served as the basic element of various techniques and methodologies used to assess the magnitude of erosion, to identify areas of excessive erosion and to project long-term changes in crop yield from soil erosion (Foster et al. 1985).

The Universal Soil Loss Equation (USLE) was derived from statistical analysis of 2,300 plot-years of data from natural runoff plots plus the

equivalent of 1000-2000 plot-years of data from rainfall simulators.
Foster et al. (1985) have summarized the development and validation of the
USLE in the United States.

The USLE was designed to predict soil loss from sheet and rill erosion
and calculate long term average annual soil losses for specific combinations
of physical and management conditions on a site specific basis. The
equation was not designed for use at regional levels but, because it is the
best and simplest available tool, it has traditionally been used for both
local and broad-scale analysis (Foster et al. 1985).

American researchers have noted certain deficiencies in the USLE and
the equation has been modified slightly over time. Foster et al. (1985)
discussed modifications that improved the equations ability to estimate
erosion from single storm events, to estimate sediment yield and to
differentiate between rill and inter-rill erosion. The literature suggests
that there are questions associated with the universal applicability of the
USLE in the United States, but that it is generally held to be unsurpassed
in utility by any other existing methods.

In Ontario, the Universal Soil Loss Equation has been used extensively
in the prediction of both existing and potential rates of erosion at large
and small scale. Wall and Driver (1982) have used erosion rates determined
by the USLE to predict the costs of soil erosion on the agricultural
industry due to yield and nutrient losses. Annual cropland soil erosion
costs were estimated to be $68 million with 80% of this loss occurring in
Southern Ontario.

Scientists have attempted to improve the applicability of the USLE in
Ontario by incorporating and accounting for the erosive effects of snow melt
in the R (rainfall and runoff) factor in the equation. This was
accomplished by adjusting rainfall erosion indicies for winter months (Wall
et al. 1983). Dickinson and Pall (1982) have also examined the erodibility
factor (K) of the USLE and concluded that it is seasonally variable with
peak erodibility occurring in late winter and early spring, under frozen
soil conditions. They note that erodibility varies most dramatically on
wet, loose silt loam with impeded internal drainage. Such conditions are
typical of the winter-spring transition period characteristic of Ontario.
American scientists also acknowledge that the USLE in its original form does
not properly account for frozen soil conditions (Foster et al. 1985). A
survey of the literature indicated that winter rainfall indices had been

corrected in the Pacific Northwest and the mountainous areas of California, to account for the erosive effects of snow melt (Evans and Kalkanis 1977). However, no studies relating to the impact of freeze-thaw on soil erosion have been found.

A methodology for mapping provincial soil loss potential has been developed at the University of Guelph (Shelton et al. 1985). The development of this approach recognized 1) the value of comprehensive regional planning in the delivery of soil conservation programs and 2) the lack of a sizeable and/or consistantly derived data base of measured erosion, suitable for use in broadscale planning. This methodology was designed to facilitate a standarized examination of predicted soil loss from relatively homogeneous soil landscape units within a regional context (Shelton et al. 1985). The Universal Soil Loss Equation is again used as a quantitative framework. Information required as input to the equation is available on a province wide basis. With the use of standardized procedures for determining representative site conditions, information is readily comparable between map units, thus allowing a ranking of problem areas. Counties with the highest potential for erosion were Middlesex, Brant, Oxford, Perth, Huron, Waterloo and Wellington (Shelton et al. 1985). This methodology provides a useful indication of relative conditions and is appropriate for use in broadscale examinations.

The Universal Soil Loss Equation has also been used in conjunction with crop yield models to predict potential average yield loss on specific soils in Huron County (Land Evaluation Group 1985). In this study, the LEM 2 grain corn productivity model, developed by the Land Evaluation Group at the University of Guelph, was used to estimate yield given soil characteristics, climatic conditions and farming practices. A discussion of LEM 2 and its possible application is presented in Smit et al. (1981). The USLE was used to estimate expected erosion on 13 selected Huron County soil series if continuous corn were grown for 25 years. In recognition of the non-uniform nature of erosion in complex topography, the estimated soil loss was assumed to occur from 25% of the area. Subsequent application of LEM 2 provided information on expected yield reductions on selected soils. The yield - related implications of the study will be discussed later in this report. With respect to soil erosion it was found that expected soil losses under the assumed conditions ranged from 2 cm to 60 cm thus illustrating the soil specific variability of erosion. The study also highlighted the variability

of soil loss tolerance between soils (Land Evaluation Group 1983). This
variability will be discussed in section 2.2.

Research conducted in 1982-83 in Wellington County and Waterloo Region
revealed that actual measured in-field erosion on specified plots was many
times that which would be predicted by the USLE (Battiston and Miller 1984,
Battiston et al. 1987). Current studies underway in Brant County by
Kachanoski and co-workers indicate instances of localized measured erosion
which greatly exceed USLE predictions. Revelations such as this draw into
question the validity of the equation for prediction of soil loss on
specific sites. Among possible explanations for this apparent failure of
the USLE are freeze-thaw processes and tillage translocation.

The freeze-thaw process is a potential contributor to locally excessive
rates of soil erosion. Repetitive freezing and thawing of surface soil,
overlaying frozen subsoil, contributes to dislodging of soil particles and
their subsequent movement. Unfortunately, a survey of the literature did
not yield any studies, Canadian or American, which have examined the role of
the freeze-thaw process in erosion.

Tillage translocation involves the movement of soil by tillage.
Quantities of soil may be moved downslope by cultivation practices (both
plowing and disking). Piest et al. (1977), in a study conducted on
loesshills in Western Iowa, found that the amount of soil moved downslope by
cultivation practices during a five-year study period were as great as
downhill soil movement by normal erosion processes. Kiss et al. (1986)
determined in a Saskatchewan study that the greatest erosion rates occurred
on the upper slope positions. They attributed this erosion to a combination
of wind and tillage. Little information is available on tillage
translocation. Aside from identifying this process, and the freeze-thaw
effect, as possible causes of localized excessive erosion little more is
possible at this time.

The aforementioned study by Battiston and Miller disputed a second
premise of the USLE - that uniform rates of erosion occur on all areas of a
given slope. This study found that severe erosion occurred in small areas
and was particularly prevalent on knolls and shoulders of slopes (Battiston
and Miller 1984, Battiston et al. 1987). In-field variations in erosion
were found to be dramatic on rolling topography. Similarly, a study
conducted in North Carolina by Daniels et al. (1985) reported that the
distribution of erosion classes (phases) on the landscape contradicted

predictions based on the USLE. While the equation predicted more erosion on the longer slopes, results showed that 49% of soils on interfluve, shoulder and linear slope positions were severely eroded.

In light of these and other observed patterns of erosion, it appears that the assumption in the USLE that erosion rates are constant in any slope position is invalid. The actual mosaic of erosional phases is non-uniform and has significant implications for field management.

American researchers note additional limitations and concerns regarding the USLE. They are summarized by Crosson and Stout (1983) and include under-estimation of erosion because of snow melt, underestimation of erosion on shallow soils because of lower infiltration, the fact that the equation was originally based on midwest soil and climate conditions and the fact that input data to the equation is often generalized or inconsistantly derived. Nevertheless, the Universal Soil Loss Equation has been, and continues to be, the fundamental tool used in the prediction of erosion at both local and regional levels. It provides reasonable estimations of relative rates of erosion and is easily used in the field by soil conservation specialists (Foster et al. 1985).

2.2 Soil Loss Tolerance

The sensitivity of soil to yield reduction as a result of erosion is determined, to a very large extent, by its physical properties. The maximum annual rate of erosion that will allow a high level of crop productivity to be maintained economically and indefinitely is defined as "tolerable soil loss" or T-value (McCormack et al. 1982). Despite the importance of this concept, information on soil loss tolerance in Southern Ontario is very limited. The maximum rate of annual soil loss which will allow the maintenance of long term productivity is generally accepted to be 7 tonnes per hectare.

Research conducted in Waterloo Region in 1982-83 by Battiston and Miller demonstrated a wide variability of T-values between individual soil series. Corn yield reductions after similar amounts of soil loss ranged from 12% on a Brant Silt Loam to 78% on a Burford Sandy Loam (Battiston et al. 1987). Similarly, a study of Huron County soils conducted at the University of Guelph (Land Evaluation Group 1983) indicated that a single value of 7 tonnes per hectare did not adequately reflect the sensitivity of all soils to long term reductions in potential productivity. Although this

study assessed only changes in physical soil properties (i.e. assumed optimum cropping and management conditions) it clearly established the variability of T-values on 13 soil types. Estimated soil loss ranged from 2 to 60 cm whereas estimated reduction in corn yield ranged from 0 to 1929 kg ha^{-1}. Based on these two studies alone, it is clear that average T-values, while of some use for broadscale analysis, are not satisfactory for specific locations.

Also included among the significant findings of Battiston et al. (1987) was the discovery of critical "total-soil-lost" levels. Little, if any yield reduction occurred with erosion until approximately 50% of the upper horizons had been lost. Continued erosion was marked by dramatic yield reductions. This study clearly illustrated the non-linear nature of the soil loss - yield reduction relationship and suggests that T-values must acknowledge the existence of critical soil loss levels on individual soil types (Battiston et al. 1987). The fact that an existing constant rate of erosion has not caused yield reduction does not imply that such a rate of loss is tolerable. The only reliable method of utilizing the concept of T-values is to determine such values on a soil-specific basis (Miller 1984).

In the United States, the concept of tolerable soil loss is one which has been utilized since the 1940's (McCormack et al. 1982). Tolerable values have been used as planning tools or targets for program managers, although their attainment has never been legislated. Guidelines for establishing T-values have been established and revised over many years. Current values used by Soil Conservation Service field advisors range from 2.2 t/ha on soils with less than 25 cm of rooting depth to 11.2 t/ha on soils with greater than 152 cm rooting depth (McCormack et al. 1982).

A review of the literature suggests that the concept of T-values, and the manner in which they are defined, has been the subject of considerable debate in the United States. Possible considerations in the setting of T-values include crop productivity, sediment yield, and phosphorus yield. McCormack et al. (1982) note that increased knowledge regarding the rate of top soil replacement, and the effects of erosion on productivity are essential to the determination of T-values based on yield maintenance. These authors further note that the inclusion of water quality objectives greatly complicate the T-value equation because of 1) the complexity of delivery-ratios, and 2) past uncertainty in the establishment of water

quality objective at both local and regional levels. For these reasons the
Soil Conservation Service in the United States has eliminated off-site
sediment damage from their criteria for determining T-values (McCormack et
al. 1982).

McCormack et al. (1982) indicate that erosion on most cultivated
sloping soil exceeds the rate of root zone formation. While T-values can be
established on technical grounds alone, most authors conclude that ethical,
economical and political consideration must also be addressed (McCormack et
al. 1982, Nielson 1986). Two options, currently being discussed in the
U.S., are the establishment of multiple T-values and the establishment of
T-values based on technical criteria, which are not consistent with
conservation objectives.

Nowak et al. (1985) and Larson (1981) discuss the concept of multiple
T-values. Briefly, this involves a T-value, based on the technical aspects
of productivity maintenance over a specified time-frame (planning horizon),
and a second T-value which accounts for the social, economic and political
costs of achieving tolerable soil loss (Nowak et al. 1985). This second
T-value acknowledges that what is appropriate from a soil science
perspective may not be attainable in reality because of socio-economic
constraints. In a similar vein, McCormack et al. (1982) discussed the merit
of T-values which reflect long-term soil productivity and acceptable
sediment yield levels. They note that the subsequent development of
"conservation objectives" would be based on the degree to which social and
political groups are prepared to achieve tolerable soil loss rates.

In summary, the literature regarding soil loss tolerance suggests that
it is the aspect of soil erosion, more than any other, which is sensitive to
both technological and socio-economic considerations. With regard to
technical improvements it is evident from studies completed in Ontario, and
elsewhere, that single or broadscale T-values do not adequately reflect the
sensitivity of individual soil types to erosion. It is also apparent that
rates of soil loss and yield reduction are non-linear and that effective
field scale soil conservation efforts must recognize not only the
sensitivity of soil types but also the proximity of erosional sites to the
critical soil loss levels discussed earlier. Further, the establishment of
T-values which are appropriate for both crop productivity and water quality
objectives requires understanding of both the soil erosion - crop yield
relationship and the soil loss - delivery ratio relationship. These will be

discussed later in this report. The literature also highlights the complexity of tolerable soil erosion and the social, economic and political considerations which contribute to its attainment.

2.3 Causes of Soil Loss and Yield Reduction

As stated at the outset of this report, the identification and implementation of effective remedial measures depends greatly on the degree to which soil conservationists understand contributing physical processes and associated impacts. Knowledge of these two areas will facilitate the selection of either corrective or preventative remedial measures.

Corrective measures are those which are designed to restore yields on currently eroded soils. In order to prescribe effective corrective strategies it is necessary to establish the causes of yield reduction.

Preventative measures are defined as those which address the soil erosion problem itself; they are long-term treatments designed to prevent further erosion and future yield reduction. The development of effective preventative measures must be preceded by an understanding of the processes and causes of soil erosion at both regional and site specific levels.

2.3.1. Causes of yield loss

The primary causes of erosion-induced yield loss are generally held to be nutrient deficiency, structural degradation and loss of available water holding capacity (Langdale and Shrader 1982, Battiston et al. 1987).

Two possible management responses to declining yield are to 1) adopt management practices which offset the effects of erosion on yields and 2) to lower erosion to a rate which permits the maintenance of soil structure and other soil properties (Crosson and Stout 1983).

The literature supports the notion that soil erosion reduces productivity by removing nutrients, and that this can, in many cases, be corrected by replacing the lost nutrients with fertilizer (Langdale and Shrader 1982). In Ontario, only two studies had been reported, prior to 1980, relating crop yield to the severity of erosion. In 1982-83 Battiston and Miller (1984) conducted extensive field work in Wellington County and Waterloo Region to examine the extent and distribution of erosion and the yield related impacts of soil erosion. Seventeen sites, exhibiting varying degrees of erosion, were studied. Eroded plots possessed lower fertility and lower available water holding capacity than non-eroded plots (Battiston

and Miller 1984). Organic matter content was lower and surface structure
less desirable with erosion. This study found that, while nutrient
deficiencies limited yield, they were rarely the only limiting factor
present. As noted above, the study found that erosion was not distributed
evenly, but occurred in small isolated areas. This scattering of erosional
areas within a field poses problems for the treatment of nutrient
deficiencies with fertilizer application. Obviously, a uniform application
of fertilizer will not be appropriate for all areas within a field; but
variable rate applications present technological and management challenges
which present research has not fully addressed.

Many studies have been conducted in the United States relating nutrient
deficiency and yield reduction. The bulk of this work was conducted in the
1950's and 1960's and is well summarized by Crosson and Stout (1983).
Almost all of these studies compared yields on top-soil and subsoil and
found that, when nutrient deficiency was the dominant limiting factor,
yields could be brought up to, or close to, yields on non-eroded top soil.

Loss of available water holding capacity (AWHC) is also identified as a
cause of yield reductions. Recent erosion productivity research in the
United States suggests that the reduction of AWHC is a more serious problem
than nutrient deficiency (Larson 1981). The literature indicates that AWHC
of eroded soils is frequently less than that of non-eroded soils and that it
is more difficult, or sometimes impossible, to correct nutrient deficiencies
when they are accompanied by unfavourable sub-soil conditions (Crosson and
Stout 1983). In Wellington County and Waterloo Region, Battiston and Miller
(1983) found that eroded sites possessing coarse textured subsoils were
unable to retain water and therefore unable to retain applied nitrogen
because of rapid leaching. Similarly, they found a high correlation between
available water holding capacity and yield at sites where moisture stress
was identified as a problem.

Ontario scientists have stated that lost available water holding
capacity, due to coarse or dense subsoil, will eventually result in
permanent and irreversible yield loss (Battiston et al. 1987). American
scientists such as Langdale and Shrader (1983) and Young (1980) substantiate
this position and state that on deep, medium textured soils principal damage
is expected to be loss of nutrients. However, technology will have little
effect on the processes by which soil is formed at the base of the root
zone. Consequently, where erosion narrows the root zone sufficiently to

reduce AWHC, technology cannot compensate for the adverse yield effect
(Young 1980). Crosson and Stout (1983) report on a study by Batchelder and
Jones (1972) in the U.S., which examined the effects of management practices
in improving the productivity of subsoils by increasing their available
water holding capacity. They found that a regime of liming, fertilization,
mulching and irrigation could be used to improve yield. While such measures
may be of benefit from a technical view point, they are not realistic for
landowners because of prohibitive cost.

Structural degradation of Ontario soils has been identified as a third
cause of yield reduction. Structural degradation is characterized by poor
drainage, ponding and poor seedling emergence. In the same manner
as lost fertility and reduced available water holding capacity, structural
degradation has been noted as a cause of yield reduction in Wellington
County and Waterloo Region (Battiston et al. 1987). This was due to a
blocky open structure in the surface horizons of eroded plots, which
resulted in poor seed-soil contact.

Soil structure is a major factor determining the ability of a soil to
allow water to infiltrate and to provide adequate aeration (Crosson and
Stout 1983). Structural degradation of a soil generally results from
compaction and/or loss of organic matter. Little documentation exists
regarding the extent of soil compaction in Ontario (Miller 1984). Miller
(1984) reports that increasing numbers of farmers now complain of soils
which are difficult to cultivate and drain.

The impacts of compaction have been studied at the University of
Guelph. Ketcheson (1980) reported observations of diminished structural
stability on continuous corn as opposed to forage-based rotations in the
1950's. Several Ontario studies completed since that time substantiated
those findings. Vyn and Daynard (1984) have investigated the effect of
alfalfa on aggregate stability and have reported that 2 to 4 consecutive
years of alfalfa caused marked increases in stability whereas 2 years of
soybeans resulted in decreased stability, relative to continuous corn
production. However, the improved stability observed when alfalfa was grown
did not persist once the alfalfa was plowed under and corn was produced
instead. Angers et al. (1987) studied the effect of four different cropping
histories on aggregate strength. The cropping histories ranged from 15 yr
of continuous corn to 15 yr of continuous bromegrass. Changes in structure
as measured by aggregate strength and inter-aggregate porosity appeared to

occur rapidly when cropping practices changed, increasing rapidly when
bromegrass replaced corn and decreasing rapidly when corn replaced
bromegrass.

Findings, such as those noted above, suggest that methods are available
to combat structural degradation. While specific measures will be discussed
in a following section, it is worth noting that, unlike loss of available
water holding capacity, it is technologically feasible to correct this cause
of yield reduction.

2.3.2. Processes of soil loss

The foregoing discussion of the causes of yield loss was based on the
need to identify corrective measures which are designed to alleviate this
major problem related to soil erosion. In addition to quickly restoring
soil productivity, conservationists must also attempt to halt the underlying
soil erosion problem through the application of preventative strategies. In
order to devise the most effective strategies it is necessary to examine the
processes associated with soil loss. These are detachment and transport.

Detachment requires energy which is provided by falling raindrops and
flowing water (Wischmeier and Smith 1965). Soil aggregates are broken down
by the impact of raindrops and primary particles are detached from the soil
mass. Much of the raindrop energy may be spent in puddling and sealing of
the soil surface, thereby increasing overland flow. Given the erosive power
of rainfall, the amount of detachment which actually occurs closely relates
to the extent to which the soil surface is protected from raindrop impact.
A complete canopy such as that provided by grasses, leaves etc. will absorb
much of the available raindrop energy and thus reduce detachment. The
canopy's ability to prevent detachment has been shown to be inversely
proportional to its height above the soil surface (Wischmeier and Smith
1978). The U.S.D.A. contends that a canopy covering 80% of the surface, at
a height of 4 metres will reduce erosion by 20%. In contrast, a full
covering of mulch at the surface will reduce erosion by 95%. While these
figures represent a broad generalization, they are indicative of the
significance of surface protection. In addition to lack of surface
protection, soils which are susceptible to detachment are also characterized
by poor surface structure.

When rainfall intensity exceeds the infiltration rate plus surface
detention, excess water moves downslope as runoff and provides

transportation for soil particles (Begg 1982, Wischmeier and Smith 1965).
Overland flow of water is generally held to be the primary method of
transport in Ontario. As noted above, it is associated with poor
infiltration, poor subsurface drainage, and concentration of flow.

Poor infiltration is associated with frozen subsoil, surface crusting
and/or surface compaction. A review of the literature reveals that
essentially no information is available in Ontario on the impact of frozen
subsoil and the freeze-thaw period on soil transport.

Poor subsurface drainage is due to naturally impervious subsoils or
subsoils which have been rendered impervious by man. In Ontario, existing
knowledge of surface soil and subsoil characteristics provides information
on the location of naturally compact subsoil but no studies have examined
the extent and distribution of man-induced subsoil compaction (Miller 1984).

Concentration of flow is a major cause of soil transport and is
associated with uncontrolled runoff and sloping topography.

Finally, transport by wind is also possible on Ontario soils. Wall and
Driver (1982) concluded that wind erosion accounted for only 2% of annual
costs associated with cropland erosion in Ontario. In localized situations
on sandy soils, however, damage can be severe. Transport of soil by wind is
related to inadequate surface protection, the removal of fence rows and
windbreaks and excessive secondary tillage (Miller 1984). In a survey
conducted by Fitzsimmons and Nickling (1982), directors of Soil and Crop
Improvement Associations in Ontario, indicated that wind erosion was an
observable problem on coarse textured soils in Kent, Elgin, Essex and
Haldimand-Norfolk Region. Corn was the dominant crop on fields in which
wind erosion had been observed although other crops are likely to suffer
from the abrasive effects of wind erosion (eg tobacco, tomatoes and beans).
Wind erosion can also be significant on organic soils used primarily for
vegetable production in the Holland Marsh, Erieau and Thedford areas.
Little research has been conducted on erosion caused by wind on Ontario
cropland. This is due, largely, to the relative insignificance of this form
of erosion in Southern Ontario.

The susceptibility of a soil to be detached and transported is defined
by Wischmeier and Smith (1965) as its erodibility. Soil erodibility is a
key input to the Universal Soil Loss Equation and has been studied in
Ontario and elsewhere. Dickinson and Pall (1982) examined the erodibility
of Brantford clay loam, Fox sandy loam, Haldimand clay (silty clay) and Fox

coarse sand. This study examined, among other things, the seasonal variation of erodibility and confirmed that greater levels of detachment and transport occurred after rainfall and/or snowmelt on soils having frozen (i.e. impervious) subsoils. Significantly higher rates were also associated with rainfall on recently tilled or thawed surface soil. Dickinson and Pall (1982) further observed that variation of erodibility was greatest on fine textured silts and clays.

2.3.3. Effect of erosion on crop productivity

Based on general understanding of the process of soil erosion and the causes of yield loss it is possible to examine their relationship and to quantify the effect of soil erosion on productivity. Methods which have been used to study soil erosion and productivity have fallen into three broad categories; scalping, direct field measurement and computer modelling. Battiston and Miller (1983) provide a useful review of each of these techniques. The following has been largely derived from their presentation.

Scalping consists of mechanically removing topsoil from a non-eroded soil. Yields are compared between mechanically desurfaced and unaltered soils. This approach was used by Ripley et al. (1961) and Englestad et al. (1961). Utilizing this method, variables in the experiment can be closely controlled. Unfortunately the physical removal of a surface horizon does not reflect the consequences of gradual natural soil erosion.

Direct field measurement involves monitoring crop growth and yields on eroded and non-eroded soils under typical field management conditions. The advantage of this method is that it occurs under actual field conditions. As mentioned earlier in this report, only one study in Ontario has involved detailed field checking on an area. Battiston and Miller (1984) found that, over a two-year period, grain corn yield on moderately to severely eroded soil was, on average, 30% lower than on areas that had experienced little or no erosion. This method of measuring yield loss, while reliable, is not frequently employed because of time and cost. This was discussed in section 2.1 of this report.

Computer modelling has become more prominent in recent years. As noted earlier in this report, the alternative to direct measurement is prediction and estimation. These tools are needed for broad-scale analysis and represent efficient approaches to assessing soil erosion and yield loss.

Much of this material has already been introduced in the earlier discussion of the measurement and prediction of erosion, and will therefore, be only briefly mentioned here. McBride and Mackintosh (1984) have developed a grain corn productivity model based on regression analysis. The model uses the USLE to estimate the quantity of soil loss that will occur on a given soil over a specified time period. It has been effectively used to estimate the effects of 25 years of erosion on 13 Huron County soils. The results of this work were summarized above.

In the United States, most early studies involved desurfacing or scalping. After 1960, field based experiments have increased in numbers. Meyer et al. (1985) provides an excellent insight into past research efforts in the U.S. and discusses the advantages and disadvantages of each form of analysis. This discussion, while very interesting, is extensive and is therefore not summarized here.

The most significant development in the United States regarding the assessment of the soil loss - yield reduction relationship has been the development of the Erosion - Productivity Impact Calculator model (EPIC). EPIC is a mathematical model for simulating erosion, crop productivity, and related processes. The intended use of the model is to determine the relationship between erosion and productivity (Williams and Renard 1985). Williams and Renard (1985) provide a detailed technical analysis of EPIC'S component parts. This paper, along with the numerous references contained therein, should be consulted by those requiring detailed information on the model.

EPIC is a very extensive process model. It consists of 53 sub-routines and 2700 Fortran Statements (Williams and Renard 1985). Its sub-routines deal with soil, water and nutrient budgets, weather simulation, tillage and residue management simulation, bio-mass crop growth simulation, soil erosion simulation and production budget costs (Crosson and Stout 1983).

The EPIC model is currently operational and has produced reasonable results under a variety of climatic conditions, soil characteristics and management practices (Williams and Renard 1983). We acknowledge the comprehensive nature of EPIC but question its practical applicability because of the formidable data demands of the model. The major limitation of all models is that they require extensive field data for development and validation (Meyer et al. 1985).

2.4 Remedial Measures

The preceding sections of this review established the economic and
environmental significance of soil degradation, particularly soil erosion.
The processes that cause soil erosion and the effects of soil erosion,
including the loss of nutrients, organic material and soil (all resulting in
loss of productivity), along with the measurement and prediction of soil
erosion were also examined. The need for remedial measures was
expressed.

An understanding of the processes that cause erosion in southwestern
Ontario and an appreciation of its effects allow the development and the
implementation of corrective and preventative remedial measures. Reducing
soil erosion will maintain and possibly improve the soil productivity and
water quality in this region. There are six broad categories of remedial
measures that may be utilized to reduce soil erosion and its effects.

1. Surface flow control
2. Subsurface flow control
3. Cropping systems
4. Tillage systems
5. Compaction control
6. Amendments

The interrelationships and interdependencies of many of these measures
usually necessitates the application of more than one measure at a time,
especially with cropping and tillage systems.

The utility of these remedial measures is dependent upon their
effectiveness and acceptability. The relative effectiveness of the remedial
measures varies with the cause of soil erosion whether it be related to
slope characteristics or compaction. The acceptability of the remedial
measures is dependent upon their affordability and profitability and the
social ramifications of management modifications.

The adequacy of the literature to address these issues as they relate to
southwestern Ontario is often insufficient. This only strengthens the need
for more studies on soil erosion in the region.

2.4.1 Surface flow control

Surface flow of water is responsible, in part, for the dislocation of
sediment and for the transportation of eroded materials. There are several
methods of controlling runoff flow, thereby controlling soil erosion and its

effects. The severity of the problem is related to the degree and the length of slope and the surface condition. Any reduction in the velocity and/or the concentration of runoff will reduce the erosive power of the water. The power of the surface flow can be reduced with either cropping and tillage practices or flow structures.

Cropping and tillage practices that increase the quantity, quality, duration or timeliness of ground cover can effectively reduce the erosive force of surface flow. Selective cropping, underseeding and interseeding, and the utilization of reduced tillage or no-till are all effective methods of improving the protective nature of the ground cover. The effectiveness of cropping and tillage practices in reducing soil losses can be increased with contour cropping and strip cropping. These practices and the examination of the pertinent literature are discussed in more detail in following sections.

Flow structures are the most permanent and often the most expensive remedial measure for controlling soil erosion. Their use is usually limited to severe erosion problems such as gullies. Surface flow structures are site specific and are dependent upon the nature of the erosion problem. Structures commonly used in the control of surface flow in southwestern Ontario include: 1) berms and diversion terraces, 2) grassed waterways and diversion channels, and 3) sediment or catch basins. These structures retain surface flow, decrease slope length or concentrate flow into protected channels. These structures are usually used in conjunction with subsurface drainage such as drop inlets. More extensive structures, such as terraces, are not commonly found in southwestern Ontario because of the difficulties associated with the region's complex topography as well as prohibitive costs for installation.

Research into the technical aspects of surface flow structures has been well established. The Soil Erosion Manual printed by the Ontario Ministry of Agriculture and Food, (1985) contains a comprehensive discussion of surface flow control structures. Included are detailed technical descriptions of vegetative and non-vegetative materials, design, relative effectiveness, and relative costs of grassed waterways, open ditches, drop structures, stream bank outlets, field terraces, diversion terraces, and water and control basins. This manual supplies the pertinent information on which to base the choice and dimensions of flow control structures in Ontario.

A cost analysis of several erosion control structures on three sample farms within the Rondeau Bay watershed is contained in the Master Erosion Control Plan for the Rondeau Bay Watershed prepared by Ecologistics Limited (1983) for the Ontario Ministry of the Environment. This report provides good examples of total capital costs and annual cost for various structures utilized to control soil erosion on the rolling loam soils of southwestern Ontario. Studies conducted by the EPA in the United States have also examined the effectiveness and the cost of implementing various flow control structures (Clark et al. 1985).

The Ecologistics report noted that the main limitation of surface flow control structures as compared to other soil erosion control measures, was the higher costs involved. Other considerations, beyond material and construction costs, that affect the acceptability of surface flow structures are maintenance, management problems, and the loss of productive land. The effectiveness of structures in erosion control, however, can be virtually unlimited.

The long-term benefits of reduced erosion may not always justify the short-term expense of flow structures, especially with an inflationary economy. The Ontario government has recognised this situation as a problem and has made assistance available in the form of loans and grants such as OSCEPAP II. Government assistance is proving successful in improving the acceptability of flow structures.

2.4.2 Subsurface flow control

The ability of water to flow through the soil determines the amount of runoff, and hence erosion. The nature of this subsurface flow is determined by the texture and the structure of the soil, and its topography.

The soil's natural drainage can be impeded by compaction: the degradation of the soil structure resulting from mechanical or chemical causes. Excessive tillage and traffic are responsible for pulverizing the structure of the soil. Porosity and aggregate size decrease and compaction results. Excessive oxidation and mineralizaiton of organic matter combined with low organic returns lower the soil's organic matter content also resulting in the degradation of the soil. The organic matter (and particularly the polysaccharides and other active constituents of organic matter) is responsible for maintaining the integrity of the soil structure and when levels are low, compaction is promoted and erosion increases.

Cropping and tillage systems are responsible for reductions in the organic matter content of the soil.

Improving the natural drainage of the soil or enhancing the existing drainage can effectively reduce the amount of erosion. The soil's natural drainage can be improved by reducing compactive activities, enhancing loosening associated with freeze thaw cycles and reducing organic matter losses by minimizing tillage or introducing crops that improve the soils natural drainage. The method, effectiveness and acceptability of such measures are discussed in the section entitled Compaction Control.

Subsurface flow can be enhanced with tile drainage or drainage ditches. The potential of drainage in reducing soil erosion has been examined by Drablos and Jones (1981). This form of remedial measure has more immediate effects but it does not prevent the infiltration problem caused by surface soil degradation. Ditching and draining may be the only remedy on fine textured, poorly drained soils where subsurface flow can not be naturally improved.

Tile drainage and drainage ditches have been widely adopted throughout southwestern Ontario because they are effective in increasing subsurface drainage, have improved timeliness of tillage, and increased crop yields.

2.4.3 Cropping systems

Cropping systems in southwestern Ontario generally involve the rotation of a narrow range of field crops. Crop rotations may include many permutations of crop sequence. Crop rotations commonly found in southwestern Ontario, in order of their relative frequency as determined by Wall et al. (1984), include:

1. row crops and cereals
2. row crops, cereal and forage
3. row crops
4. row crops and forage
5. cereal and forage

The crops included and the duration of the sequence is strictly a managerial preference involving many factors such as relative profitability, pest control, nutrient levels, pesticide residues, labour distribution, and productivity. Erosion control has only recently been a major consideration when planning a cropping system.

The production of any grain crop requires a reduction in the amount of ground cover from that of natural field conditions. This reduces competition, controls disease, and makes many managerial functions such as weed control easier. Reducing the amount of ground cover leaves a greater proportion of the soil unprotected from erosive elements thereby increasing erosion. The problem of erosion is compounded by tillage and its effects on the soil. Cropping systems have conventionally involved intense cultivation. Tillage practices, their impact on erosion, and their relationship with cropping systems are discussed in the following sections.

A good ground cover, which includes vegetation cover and/or residue, effectively controls erosion because it reduces the amount and concentration of wind and water flow over the surface, and stabilizes the soil making it less erodible. The ground cover also absorbs the energy of the falling rain drops which are the major cause of soil particle dislocation. Canopy cover is most effective in this capacity when it completely covers the soil surface below. The lower the cover is to the ground the more effective it is in absorbing the total rainfall energy before it reaches the soil. Complete ground cover at ground level can reduce erosion by up to 95 percent (Wischmeier and Smith 1978). The effectiveness of the ground cover is most easily observed on steep slopes.

The choice of crop determines the quantity, quality, duration and timeliness of the canopy cover. The choice of crop also affects the nature of the residue. Some crops produce more total residue and some decompose more slowly because of high carbon-nitrogen ratios (Mannering and Johnson 1976). The amount of residue is largely determined by the tillage practices associated with the cropping system.

Forages are the most effective crop in reducing soil erosion because they have an extensive root network, sustain dense growth throughout the growing season, have a long growing season, supply a good ground cover throughout the winter, and are close to the ground. The inclusion of perennial forages into a cropping rotation is regarded as a very effective erosion control measure (Ketcheson 1977, Wischmeier and Smith 1978, Ketcheson 1980). The positive residual effect of a grass-legume meadow which is tilled diminishes within a 2 to 3- year period. A mixture of grasses and legumes were more effective than legumes alone (Wischmeier and Smith 1978). Even the inclusion of small grains into a row crop rotation can be an effective measure in reducing soil erosion. Row crops are most conducive to soil erosion because they are seasonally grown, provide only

partial canopy cover during much of the growing season, and provide channels
for concentrated flow. Limiting the number of years of row crops in
rotation, particularly of corn and soybeans, would definitely be beneficial
to soil erosion control, but the relative profitability of some row crops,
their importance as lovestock feed, and the need for crop diversification
make that an unacceptable measure.

There have been several studies conducted in southwestern Ontario that
demonstrate the detrimental effects of a continuous corn rotation. On more
sloping, medium textured soils in continuous corn, Webber (1964), measured
soil losses as high as 70 tons per acre in a single year. Corn in rotation
with a sod crop suffered less than one-third of this soil loss. Runoff
plots at Guelph and Ottawa have shown that the rotation of corn, cereals,
and hay can reduce soil and water losses to a fraction of the losses with
continuous corn. A corn-oats-hay-hay rotation had one-tenth and one-third
the soil losses as compared to continuous corn on loam and clay soil
respectively (Ketcheson 1977). Yield benefits were also shown possible from
improved soil physical conditions and nutrient supplies (Webber 1964).

Results obtained from a study by Baldock and Kay (1987) indicate that
15 years of continuous grain corn production using conventional tillage
practices significantly reduced the size and water stability of soil
aggregates relative to 15 years continuous bromegrass production. Probably
of more importance is the fact that the rate of loss of structural stability
induced by grain corn production was faster than the rate of gain induced by
bromegrass production. A similar study on the effects of crop sequence on
soil structure, stability and productivity was conducted by Vyn (1987).
Tests were performed on two sites between 1980 and 1985, one a silt loam
soil near Elora and the other a clay loam near Milton. Soil cropped with
continuous alfalfa was consistently higher in structural stability than soil
in continuous corn. Interestingly, soil structural stability during the
first year of alfalfa was not significantly better than that of continuous
corn. This indicates the cumulative nature of costs and benefits associated
with these two extremes. Vyn (1987) also found that in a short term
rotation, corn yields could be maintained so long as corn followed something
other than corn. Apart from soil degradation and soil loss, continuous corn
production suffers substantial yield losses under no-till on poorly drained
soil. A rotation of crops was found to remedy the yield losses of
continuous corn on poorly drained soils (Van Doren et al. 1976, Dick et al.

1986). More research is needed on crop rotations other than continuous
corn. Wall et al. (1984) note that continuous corn accounts for only 8% of
cropland in southwestern Ontario. Continuous corn has been given a
disproportionate amount of attention.

One rotation which is worse than continuous corn, is a soybean-corn
rotation. Researchers in Iowa have shown that plots planted to corn
following soybeans were 40% more erosive than situations where soybeans
followed corn or corn followed corn using conventional tillage (Mannering
and Johnson 1976). Soil losses in the spring are much greater following a
crop of soybeans than following a crop of corn. Soybeans do not produce a
large amount of residue and the residue which is produced decomposes faster,
in part because of a low carbon-nitrogen ratio. Soil aggregate stability is
also generally lower after soybeans than after corn (Bathke and Blake, 1984;
Kladivko et al., 1986). Mannering and Johnson (1976) suggest that the
residual effects of the previous crop may have more influence on soil
erosion than the present crop. This has significant ramifications when
considering tillage systems.

Crop rotations can also reduce production costs. Rotations disrupt
weed, disease and insect cycles, reducing the need for high pesticide
application (Clark et al. 1985). A short term profit may not be seen unless
there is a market for all the crops in rotation.

The pronounced seasonal climate of southwestern Ontario results in
seasonal erosive activity. Soil is most susceptible to erosion in the
spring, following freeze-thaw processes and when precipitation is high
(Dickinson and Pall 1982). For this reason the duration and the timeliness
of the ground cover is of the utmost importance (Frye et al. 1985).
Consideration of these facts has led to the modification of standard
cropping systems beyond the simple inclusion of forages and small grains.

Underseeding and interseeding have become popular methods of reducing
soil erosion, particularly at critical times of the year, and retaining row
crops in rotation (Wischmeier and Smith 1978, Clark et al. 1985).
Underseeding is the growth of a dense low-lying secondary cover crop, such
as red clover, rye, vetch and alfalfa, under a more predominant primary
crop, such as wheat or corn. Underseeding is already a common practice with
winter wheat production; research indicates that higher soil aggregate
stabilities are achieved when wheat is underseeded with red clover than when
wheat is not underseeded (Vyn, et al. 1984). Interseeding confines the

secondary crop to the inter-row space of wide-spaced row crops such as corn
and soybeans. Studies into the relative success of red clover and alfalfa
interseeded into corn at the University of Guelph, by Vyn et al. (1984),
found that red clover established a better stand and achieved higher yields
than alfalfa when interseeded. However, corn yield depressions were
sufficiently high to discourage this practice in grain corn production.
Research by Sheard (1987), also at Guelph, on silage corn underseeded with
red clover concluded that red clover reduced the nitrogen requirements of
the corn, but the monetary gain derived from the reduced N requirement was
counter-balanced by the slight yield depression. The benefit was
insufficient to pay for the cost of the red clover seed. The benefit of
reduced soil loss was not assessed.

These secondary crops remain through the harvest of the primary crop
and persist as a protective cover until late fall or spring when they are
killed and plowed down. Competition problems are reduced by planting slowly
developing secondary crops with the primary crop or planting after the
primary crop has been established. Vyn et al. (1983) noted that when
alfalfa and red clover were seeded on the same day as corn, corn yields were
significantly lower due to competition. Later interseeding was found to
reduce competition but establishment of the legume was also much more
erratic.

As well as reducing erosion, underseeded and interseeded cover crops
provide substantial amounts of organic material and, in some cases, nitrogen
to the soil. However, the presence of a cover crop may result in conditions
that are conducive to weeds, diseases, and insect pests (Power 1983). Power
notes that research on legume/weed-disease control is limited. Research at
Michigan State University has demonstrated that rye residues release
chemicals which supress the growth of certain weeds. Certain types of wheat
and sorghum were also found to have this effect (Anon. 1984). The effects
of various cover crops on management practices need to be examined in
greater detail.

The production of phytotoxins from cover crops is a matter of concern.
Prior to planting, the cover crop is killed by tillage or herbicide
application. During decomposition, components in the decompositionary chain
may accumulate to toxic levels. The rate of decomposition, and hence
phytotoxin production, is dependent on soil-climate-relations and therefore
is very site specific. Corn yield reductions of 10 to 25% have been

observed at Elora and Woodstock following fall rye cover crops (Muldoon et al., 1985). Corn yield reductions were observed whether the rye was plowed, disced or chemically controlled. Preliminary studies are being conducted by the University of Guelph in Huron county on phytotoxin production in wheat stubble and its affect on no-till corn. The complexity of choosing a productive rotation greatly increases when factors such as this are considered. More information about phytotoxins is contained in Martin and Touchton (1983).

All of these remedial cropping measures provide significant erosion control from surface runoff, and the increase in organic matter production can improve the soil structure and stability, possibly alleviating compaction, increasing infiltration which reduces runoff, and further reduces erosion. The effectiveness of cropping systems in alleviating compaction and the associated reduction in erosion is discussed in the section Compaction Control.

Other cropping practices that can be utilized in the reduction of soil erosion include contour strip cropping and buffer strip cropping. Contour strip cropping is a practice in which contoured strips of sod are alternated with equal-width strips of row crops or small grains. This practice is more effective than contouring alone. The seeding of eroded areas to perennial grasses and legumes is called buffer strip cropping. It is less effective than contour strip cropping (Wischmeier and Smith 1978).

2.4.4 Tillage systems

The tilling of soil, conventionally, has several purposes, including:

- weed control
- control soil-borne insect pests and diseases
- incorporate pesticides and amendments
- loosen compacted soil to improve aeration
  and water infiltration
- decreases aggregate size to prepare a favourable seedbed and
  rootbed
- dry and warm the soil
- manage residue

Although conventional tillage systems are usually quite successful in achieving these ends, they have their drawbacks, the most important to this study is increased soil erosion. The type, frequency, and timing of tillage

operations influence porosity, roughness, cloddiness, compaction, and
microtopography. Tillage also affects water intake, surface storage, runoff
velocity, and soil detachability, all of which are factors in potential
erosion (Wischmeier and Smith 1978).

The oxidation of the soil reduces the organic matter content and
impedes the particle bonding of microorganisms, and a decline in the
aggregate stability ensues. Bulk density increases and soil porosity
decreases, restricting aeration and water movement. Root growth is
retarded and surface runoff is promoted. The impacts of compaction and
nutrient deficiency, and their remedial measure are discussed in later
sections.

Most tillage operations reduce ground cover, particularly crop residue,
and increases the exposure of soil to the erosive elements. Residue is
often more important in controlling soil erosion than vegetation cover.
Residue may cover less surface area than a closed canopy cover but, because
it is lower to the ground, it is more efficient in absorbing rain energy and
it persists as a protective cover for a greater portion of the year
(Wischmeier and Smith 1978). The type of tillage system determines the
amount of the residue left on the soil surface.

The quantity of residue left on the surface is the dominant factor in
the effectiveness in reducing soil erosion. Residue breaks the surface flow
of water reducing its erosive power. It increases the retention time of
surface water thereby increasing infiltration. Increases in the organic
matter content near the soil surface improve the soil structure and natural
drainage which in turn, increases the infiltration rate (Frye et al. 1985).
Residue provides a protective cover for the soil in early spring when the
soil is most susceptible to erosion. It also retains snow in the winter
altering the freeze-thaw processes and spring meltwater conditions.

There are many forms of tillage systems utilized in southwestern
Ontario, the most common of which is the conventional tillage system.
Convention tillage is the most intensive tillage system and includes primary
and secondary tillage, followed by planting. Primary tillage in
conventional systems consists of fall moldboard plowing. Secondary tillage
includes spring disking (once or twice) and/or spring tooth cultivation
(once or twice). Because conventional tillage is the most intensive it is
also potentially the most degrading to the soil.

Narrow row crops, such as wheat and barley, allow no post-plant

cultivation. Meadow crops are usually perennial and are not maintained with
tillage. Row crops, such as corn and beans, require the most intense
tillage and suffer the greatest soil losses from its effects. "There is a
universal conviction among agricultural researchers that intense tillage,
as it is practiced today (conventional), is the main cause of erosion"
(Hoechst 1984). This would suggest that the best way to control soil
erosion would be to utilize less intense forms of tillage on crops or
include crops that require less intense tillage.

Alternate forms of tillage that reduce soil erosion are collectively
called conservation tillage. Conservation tillage includes reduced tillage,
strip tillage, ridge tillage, minimum tillage, and no-till or zero-till.
All forms of conservation tillage reduce the intensity of tillage practices
and/or change the timing of tillage in comparison to conventional tillage
practices for the purpose of reducing soil erosion by increasing the amount
of residue left on the surface, especially at critical times of the year.
The effectiveness of these tillage practices in controlling soil erosion and
their impact on productivity vary with soil texture.

No-till is the most extreme form of conservation tillage. The only
tillage required is in the actual placement of the seeds during planting.
No-till requires less traffic in the spring when the soil is most
susceptible to erosion. The maximum amount of residue is left on the soil
surface and the maximum erosion control is achieved. The increased bearing
capacity of untilled soil allows the surface to be trafficked in wetter
conditions. This can be especially important in late fall harvests when
heavier machinery is used and the soil is high in moisture content. A
complete discussion of no-till and the other forms of conservation tillage
can be found in Hayes (1982) and Young (1982).

There has been extensive research undertaken to evaluate these tillage
practices under various conditions. Most of the data on the impact of
tillage on erosion in Ontario has been obtained from runoff plots at the
University of Guelph. A series of ten plots has been in operation since
1952 and has been used to measure the effects of different management
systems. Ketcheson and Webber (1978) reported that, over a six-year period,
continuous no-till corn with stover left reduced soil loss to less than 0.01
cm/yr. By comparison, the greatest losses occurred when stover was removed
and plots plowed in the fall. No-till markedly reduced erosion although it
did not reduce runoff to the same extent. Although conservation tillage has

been shown in these and other studies to effectively control erosion on uniform slopes, Battison et al. (1987) found much more severe erosion on the shoulder slope positions. Essentially no data are available on the effectiveness of remedial measures in controlling erosion on these slope positions.

A large proportion of the tillage research done in Ontario has been with corn on medium and fine textured soils. Vyn, Daynard and Ketcheson (1979 and 1982) focussed research on long term tillage experiments for corn production on four soil types, sandy loam, loam, silt loam and clay loam. Yields with zero tillage in these studies have averaged about 15% lower than those with conventional tillage when corn followed corn in rotation. When corn followed crops other than corn, yields were not as drastically reduced (Vyn, Daynard and Ketcheson 1979 and 1982). Subsequent research suggests that yields with no-till may be improved when discs or blades are used on the planter to remove residue from the row area. Researchers have noted that spring rather than fall plowing, may be an effective method of controlling erosion during this critical period (Vyn, Daynard, Ketcheson and Lee 1982, Miller 1984). Crop research has demonstrated, however, that, on finer textured soils, fall plowing is necessary to produce a suitable seedbed (Vyn, Daynard and Ketcheson 1982). The same research has also demonstrated that, on fine textured soils, there was no yield advantage related to excessive secondary tillage if soils were sufficiently dry at the time of tillage.

Many studies have been conducted, throughout the United States, involving various tillage systems on various soil types. Included in a special conservation tillage edition of the Journal of Soil and Water Conservation in 1983 are studies by Mannering and Fenster, Moldenhauer et al., Cosper, and others. This journal issue contains papers on many aspects of conservation tillage. Allmaras et al. (1985) summarize several other studies on conservation tillage.

Studies of tillage-planting systems in Ohio have documented the relationship between soils, tillage systems, crop yields, and soil erosion (Allmaras et al. 1985). Van Doren et al. (1976) showed that differences in corn yield with conventional and no-till systems were affected by soil type, immediate past cropping history/tillage intensity, and time. In the Ohio studies three cropping systems were used; continuous corn, corn-soybeans in a two-year rotation and corn-oats (seeded to alfalfa)-meadow in a three-year

rotation. Various tillage techniques, ranging from moldboard plowing to no-till, were employed and tests were conducted on both fine and medium textured soils (Van Doren et al. 1976, Dick et al. 1986).

On fine-textured soils, corn yields were found to be consistently lower over a 22-year period where no-till was applied to a continuous corn cropping system. Yields were also reduced with a combination of reduced tillage and continuous corn. In rotations involving soybeans and oats, yields were slightly lower with no-till. It was found however, that most of the reduced corn yield could be recouped if either crop rotation or tillage were applied. Researchers also found that after 19 growing seasons, both tillage and rotation showed a significant effect on soil fertility (Dick et al. 1986). No-till plots were found to be lower in pH but enriched in organic matter and plant nutrients in the upper 7.5 cm. Conversely they contained lower concentrations in the lower portions of the plow layer. These differences were attributed to the broadcast application of fertilizer without mechanical incorporation. Researchers did not attribute yield variation to the observed stratification of nutrients.

Research on medium textured soils in Ohio has been summarized by Van Doren et al. (1976). With regard to crop rotation it was found that lowest yields of corn were associated with continuous corn and the highest with a three-year rotation of corn - oats - meadow (Van Doren et al. 1976). During the initial six years of this study, 40% of all no-till plots experienced problems with yield and weed control. Over the remainder of the study this "problem rate" was halved indicating significant progress in no-till technology. Generally, it was found by Van Doren et al. (1976) that corn yields on medium textured soils were relatively insensitive to tillage over a range of soil types, climate, cropping system and past history so long as equal plant densities and adequate weed control had been achieved. Selected no-till sites were observed to have suffered substantial yield losses on poorly drained soils but only when in continuous corn (Van Doren et al. 1976). Finally, some situations of improved yield with no-till were observed. These occurred on well drained sloping soils and were associated with conservation of moisture and improved soil structure. Allmaras et al. (1985) summarizes other studies conducted in Indiana and Illinois. Findings are similar to the Ohio studies just discussed, and will not be examined further. Included among their findings were the trend for poorer yields for no-till corn on poorly drained fine textured soils and equal or improved

yield for no-till corn on medium textured, well drained soils. These same trends were evident for two-year rotations including soybeans but yield reductions were less dramatic (Allmaras et al. 1985).

Under the conservation tillage system, many of the objectives of tillage identified at the outset have to be met through other management practices. The most significant in southwestern Ontario is an enhanced pesticide programme. Management systems become more complex. New equipment has to be developed and old equipment has to be modified to deal with the changes in tillage. One of the most significant changes is in planting equipment. It has to be able to plant into large quantities of residue and it has to able to effectively apply fertilizer. Erbach et al. (1983) and Murphy (1983) discuss many of the technological developments associated with conservation tillage systems. The success of conservation tillage is dependent upon the effectiveness and acceptability of these changes.

Apart from the effectiveness of conservation tillage in reducing soil erosion, Hoechst (1984) and Crossman (1981) identify other benefits which make it more acceptable than conventional tillage. They include:

- reduced labour
- redistribution of labour
- reduced equipment maintenance and cost
- reduced fuel use
- maintenance of optimum organic matter content in the soil
- declines in some weed populations
- greater moisture retention

Both authors discuss these benefits in comprehensive detail. Hoechst cautions that all of these benefits will not be seen under all conditions.

There are other tillage practices that may be effective in controlling erosion without drastically changing cropping and tillage systems. Contour tillage, by increasing the cross-slope surface roughness, will retain surface flow and promote infiltration. Contour tillage does not lead to the concentration of flow downslope as does tillage with the grade. Researchers have concluded that surface residue cover is a more effective erosion control measure than surface roughness (Vyn, Daynard and Ketcheson 1982, Vyn, Daynard, Ketcheson and Lee 1982). The acceptability of contour tillage in southwestern Ontario as noted above, is limited by the often complex topography in the region.

An extensive on-farm research-demonstration programme, called Tillage-2000, is being conducted jointly by OMAF and the Dept. of Land Resource Science at the University of Guelph. The goal of the programme is to develop and evaluate conservation farming systems for specific soil types, which maximize economic productivity and minimize soil degradation.

This study is more comprehensive than previous studies in Ontario because it goes beyond tillage systems; it is looking at the integration of conservation tillage practices with other conservation practices. Tillage-2000 was initiated in 1985 and now consists of 31 farm cooperators. Each study site has two treatments, a conservation and conventional tillage system. Paired permanent benchmark plots have been established for collection of data from each tillage system. Each of the permanent benchmark locations will be characterized with respect to topographic and soil properties. In addition to the one time detailed soil and topographic measurements, soil and crop data are collected each year from each benchmark. Measurements include crop yield, crop growth characteristics, emergence and population counts, surface residue cover, weed counts, soil fertility, pest and disease observations. For each treatment, information regarding most aspects of operation are recorded. These include type and use of equipment, estimated fuel consumption, herbicides, pesticides, seeding rates and date, fertilizer, and growing season rainfall. Soil erosion is measured with 137-cesium tracer which was discussed in the section entitled Measurement and Prediction.

Data has been collected for only one growing season and specific recommendations cannot be made. However, preliminary analyses indicate the conservation system was very successful. The average yield indices (conservation yield/conventional yield) were 1.0, 0.97 and 0.95 for sites with coarse, medium and fine textured soils respectfully. Economic analysis indicated a significant savings in time and cost per bushel for the conservation systems (Aspinall et al. 1987).

In a similar study with corn in Ohio (Honey Creek Watershed Project 1981) no-till yields were 10% lower than conventional tillage and the cost of production per bushel was 14% higher.

A number of more detailed studies are also being carried out in Tillage-2000. These include nitrogen response of corn under conventional and no-till systems and herbicide studies. Results of these studies are also preliminary.

A project similar to Tillage-2000 has been carried out for the last six years in Saskatchewan and is called Innovative Acres (Farm Lab project, Rennie et al. 1982). This project is administered by the Dept. of Soil Science, at the University of Saskatchewan. The objectives of this project are to maintain soil quality and productivity by developing water efficient farming practices. The emphasis on crop water-use is related to the dryland farming conditions in Saskatchewan. The programme utilizes the same concept as Tillage-2000 with paired farming systems being established on forty farm cooperator sites. Paired benchmarks were used within each farm site similar to Tillage- 2000. The goal with the Innovative Acres, as with Tillage-2000, is to bridge the gap between intensive plot-scale research and field application of the developed technology. Farming systems, not specific treatments are evaluated.

2.4.5 Compaction control

Soil compaction is the result of deterioration of the soil's natural structure and stability. It is a major form of soil degradation, often resulting in loss of soil and productivity.

The increase in soil bulk density and the decrease in macropore space associated with compaction are responsible for the reduction in oxygen diffusion and water infiltration, and the retardation of root development. The reduction in infiltration results in increased surface flow which in turn increases soil erosion. Soil compaction ultimately results in the reduction of the soil's productivity.

In a regional study of Canada by Rennie (1985), the annual profit lost in Ontario due to compaction was estimated at 21 million dollars (erosion = $68 million/annum) as compared to Quebec which had an estimated annual loss in profit of 100 million dollars (erosion = $10 million/annum). Rennie did not state how much of the losses due to erosion were compaction induced. Although the greatest contribution to Ontario's compaction related loss in profit is expected to come from Eastern Ontario, soil compaction in southwestern Ontario is no doubt a problem and definitely deserves consideration.

The significance of soil compaction in southwestern Ontario has not been well established. It is often overshadowed by the more obvious forms of soil degradation related to soil erosion. Wall et al. (1985) noted the great variation in the awareness of farmers in eleven counties in

southwestern Ontario to soil compaction. In some counties the awarness was as high as 69% (Essex) whereas in most of the eleven counties less than forty percent were aware af soil compaction problems. The perceived significance of the problem was not determined. Soil compaction is clearly not recognized as a major problem in southwestern Ontario. This accounts for the lack of research into soil compaction, its effects, and its relationship with soil erosion.

The potential problem of soil compaction in southwestern Ontario, particularly with regards to soil erosion, has been realized by researchers but an assessment of the problem has not been available to date. Bolton et al. (1979) found that the practices involved in a continuous corn cropping system in southwestern Ontario had a detrimental effect on both the total and air-filled pore space, causing compaction. The promotion of erosion was not evaluated but compaction was responsible for reducing the uptake of nutrients. The processes and mechanics of soil compaction in southwestern Ontario are not fully understood. Without this understanding an evaluation of the problem is not possible, and proper remedial measures can not be taken.

Research has been initiated but it still remains in its preliminary stage. McBride at the University of Guelph is conducting laboratory studies on the mechanics of compaction and Vyn (Guelph), as well as Baldwin (Ridgetown) are conducting field studies on compaction. Kennedy, a Soils and Crops Specialist with OMAF, is looking at the problem of compaction on the flat, fine textured soils of the Stratford area in Perth county.

The greatest volume of research on compaction, its degrading influence on soil, its relationship to soil erosion, and remedial measures, pertinent to southwestern Ontario comes from the Great Lakes States. Prominent American researchers include Voorhees, Lindstrom, and Dickey.

Soil compaction is caused by the reduction in the soil organic matter content and/or the mechanical pulverization and compaction associated with management practices. Apart from the influence of cropping systems on organic matter input, tillage is generally responsible for changes in the quantity and quality of the soil organic matter content. It oxidizes the soil, decomposing the organic matter (Voorhees 1979). A decrease in organic matter and microbial activity results in instability, poor aggregation of the soil structure, and lower AWHC. The bearing strength of the soil is reduced. When the load of machinery exceeds the bearing capacity of the

soil, compaction occurs. Tillage is also responsible for the pulverization of the soil structure. High axle loads often associated with harvesting or manure application and operations in situations where soil has a high moisture content are prime offenders.

Subsurface compaction is caused by forces that extend deeper than those of surface compaction. This deep compaction is induced by driving on or tilling a soil that is too wet with heavy equipment. Field studies done in Minnesota show that axle loads of between 10 and 20 tons compacted a clay loam soil to a depth of one metre (Anon. 1985). Typical tractor weights are about 20 tons (Voorhees 1986b). Harvesting equipment exceeds 20 tons per axle (Dickey et al. 1985a).

The degree of compaction is dependent upon soil type. Fine textured soils retain a high moisture content for a relatively longer portion of the tillage season and are therefore a greater concern than coarser soils. The weaker structure of fine soils makes them more susceptible to mechanical compaction (Dickey et al. 1985a, Voorhees 1986a). For these reasons soil compaction is a more prevalent problem on flat, fine textured soils such as those found in Kent, Essex and Perth counties. Coarser textured soils are not free from compaction but more obvious degradation due to erosion, related to their typical geomorphology (complex topography of glacial deposits), dominates.

Natural forces that expand and contract the soil work to alleviate compaction. Freeze-thaw processes and the wetting-drying of clay loosen the soil. These processes are slow and their effectiveness is determined by the extent of the process, their depth, and the number of cycles. Fracturing and aggregation of the soil can be caused by root growth. The stability of the improved state is governed by the organic matter. Research by Voorhees (1983) indicated that these processes may be limited below depths of 20 cm. Research in Minnesota showed that freezing and thawing broke up only half the compaction in the upper 8 cm of the soil and less than one quarter of the compaction in the upper 30 cm. Freezing and thawing, therefore, is generally considered ineffective at reducing subsurface compaction (Dickey et al. 1985b). There is some evidence from the University of Guelph that frost action may only temporarily alleviate compaction. Soil was found to quickly reconsolidate upon thawing and return to near pre-freezing bulk densities prior to spring planting (Kay et al. 1985). Where natural alleviating forces are insufficient, remedial measures must be taken to

control compaction and reduce soil erosion.

Remedial cropping and tillage practices are considered effective in controlling compaction. Choosing crops that require less intense tillage, particularly at critical times of the year, can be effective in reducing compaction. Whether or not reduced tillage systems reduce traffic is questionable because they require increased pest management, but the traffic is displaced from the spring period.

Voorhees studies cited in this paper point out a very important factor when considering changes to existing management practices. If tillage is reduced, not only are many of the compactive activities eliminated, most if not all the practices that alleviate compaction are eliminated. If natural forces are insufficient in alleviating compaction, reduced tillage systems may actually increase compaction, and soil erosion.

Voorhees and Lindstrom (1983) have questioned the effectiveness of reduced tillage in controlling compaction. Because the first pass over the field in multiple pass systems accounts for 75 to 90 percent of compaction, reducing the number of tillage passes has a minimal effect. Secondary tillage does not account for a significant portion of the total compaction. No-till reduces the amount of wetting-drying cycles, therefore it also is considered to have a limited effect because it lacks the alleviating forces of both tillage and nature.

Tillage, although it causes compaction, also acts as a corrective measure to alleviate it. The effect tillage has with regards to compaction depends upon the soil water content, the soil type, and the kind of tillage operation (Voorhees 1983).

Reduced tillage systems because of their shallower depth and less intense disturbance were essentially no more effective in reducing penetrometer resistance or bulk density than natural forces (Voorhees, 1983). Voorhees (1983) cited Lindstrom, 1981, who, based on high penetrometer resistance and bulk density, stated that no-till soils may have significantly lower infiltration rates which could eventually result in runoff problems in the spring even though it does provide soil erosion control. But in a no-till system, the extensive network of biopores give much greater infiltration than is normally expected for a given bulk density and penetrometer resistance (1983).

Deep cultivation with plows or subsoilers can remedy the compaction problem. This practice may be common in the United States but in

southwestern Ontario it is not. The success of deep cultivation is highly variable.

Varying the depth of tillage from year to year will impede the development of a compacted layer. Any tillage system, including no-till, can lead to the formation of a compacted layer if it is performed at the same depth year after year (Dickey et al. 1985b).

Voorhees (1983) reported that soil compaction caused by wheel traffic during the growing season can be alleviated to varying degrees by natural forces and autumn plowing. In his research Voorhees observed a 50 percent reduction in the penetrometer resistance in the tilled layer of a compacted soil from natural weathering forces. The value of 50 percent was dependent upon the soil water content, higher moisture content results in greater frost action. Moldboard plowing together with natural forces decreased both the penetrometer resistance and the bulk density of the tilled layer of the compacted soil to essentially the same level as an untrafficked soil.

Controlling traffic is an effective measure for controlling compaction. Permanent traffic lanes can be established to limit the amount of compacted area. Under conventional tillage systems as much as 90% of a field may be driven on at least once a year (Dickey et al. 1985b). Because the first pass over the field results in approximately 80 percent of the total compaction, restricting all subsequent passes to those of the first field operation also reduces the total compaction (Voorhees and Hendricks 1977). Implement sizes have to be matched so that all wheel tracks are in the same inter-row space year after year. This may result in unacceptable costs. However, traffic control can reduce energy costs. The energy requirements on a compacted soil are less than a loose soil because there is less rolling resistance and more traction (Voorhees and Hendricks 1977). The acceptability of this practice is very limited because of its increased management restraints.

In an attempt to reduce the number of passes over a field, many functions may be instrumented at one time but greater sizes of machinery are required. Larger machinery means greater loading on the soil increasing the compaction per pass. The size of machinery required for a no-till system is generally less than a conventional system because many of the heavier practices are eliminated. Reducing axle weight decreases the compactive force but reducing machinery size often means reducing efficiency and increasing costs.

Dual wheels can be used to decrease the severity and depth of compaction, only if the extra floatation is not used to work soils that are too wet to work without it. The compaction with duals is spread over a larger area though the total amount of compaction does not change (Dickey et al. 1985b).

Headlands are the most heavily trafficked portion of a field. Severe compaction and erosion can sometimes occur on these areas making them unproductive. If this is the case headlands may be best left untilled and possibly under a permanent cover crop. This would reduce compaction and control erosion without greatly affecting their profitability.

Practices that return high quantities of organic matter to the soil are beneficial to the soil structure. Certain crops, such as alfalfa, included into rotation have been found to increase the bearing capacity of the soil and alleviate compaction because of their extensive root growth and high organic return (Angers et al., 1987).

Where compaction can not be controlled, measures can be taken to offset its effects such as artificially improving the drainage. These measures are examined in section 2.4.2, entitled Subsurface Flow Control.

Voorhees (1979) has put the necessity of alleviating compaction into some doubt by demonstrating that compaction does have some benefits in reducing erosion and increasing productivity. Voorhees has suggested that soil compaction offsets the effects of decreasing organic matter on aggregate stability. The cloddiness of tilled compacted soil may reduce runoff and increase infiltration. Compaction will provide less erosion control on light texture soils where clods do not develop (Voorhees 1977a). Compaction may also improve the soil moisture condition in a dry season by decreasing evaporation and increasing capillary action transport (Voorhees 1977a). Voorhees does acknowledge the bad effects of compaction discussed in this review and states that wheel-induced compaction may do more harm than good (Voorhees,1977a, Voorhees 1977b, Voorhees and Hendricks 1977).

2.4.6 Amendments

Amendments to soils in southwestern Ontario are usually in the form of fertilizers or organic matter. They are applied to overcome detrimental effects of soil erosion, two of which are the loss of available nutrients and loss of organic matter content. Amendable nutrient deficiencies commonly associated with soil loss are N, P, K, and Zn (Batchelder and Jones

1972). The organic matter content can be increased with the addition of manure or the return of crop residue. Both of these effects of soil erosion ultimately reduce the productivity of the soil which make their remedy an economic concern.

Batchelder and Jones (1972) examined the ability of amendments to improve the productivity of eroded soils by increasing available nutrients and increasing the AWHC. To simulate severe erosion conditions on very fine sandy loam and clay loam soils of North Dakota, they stripped off the topsoil exposing the subsoil. They were able to directly compare the influence of fertilizers and mulch amendments on similar 'eroded' and non-eroded soils. Amendments to the subsoil were found to equal or improve productivity in relation to the unaided topsoil. Crosson and Stout (1983) have noted similar studies conducted in southwestern Iowa on Marshall and Monona silt loam soil. The conclusions of such research indicate that amendments to eroded soils can improve crop yields to at least equal to those of non-eroded soils when nutrient deficiency was the only limiting factor.

The problem with these studies is that the 'non-eroded' soils are not at their optimum productivity and therefore should not be directly compared to amended eroded soils. All soils under cultivation require amendments of varying degrees to sustain a high level of productivity. Olson (1977) found where equal amounts of fertilizer (N, P_2O_5, K_2O, Zn) were added to a Beadle silty clay loam typical of many glacial till soils in eastern South Dakota and western Minnesota that the non-eroded soil had higher corn yields. On an average of the six treatments over eight years, yields on the undisturbed soil were 37 percent above yields on the eroded soils. Fertilizer compensated for some but not all of the yield decrease incurred by topsoil removal. Olson concluded that simply adding nutrients to severely eroded soils may not restore the soils original productivity. Other factors, such as available water holding capacity, affect the productivity of soils (Battiston et al. 1987).

Results from erosion studies by Frye et al. (1982) on two Kentucky soils also suggest that neither low-intensity use, nor optimum fertilizer amendments can restore a strongly developed soil to its original production potential after it has been damaged by erosion. Although the productivity may be increased on eroded soils through management, the productivity of severely eroded soils may never be restored to their original non-eroded

state. Frye et al. (1982) cite another study with similar findings.

In general, amendments are not very effective in reducing soil erosion, they merely offset its effects. The application of organic matter, however, increases the organic matter content which promotes aggregation and infiltration, both reducing erosion (Olson 1977). Increases in organic matter generally increase the total water-holding capacity of the soil as well as the water supplying capacity of the soil, but apparently does not increase available-water-holding capacity, except in sandy soils (Frye et al. 1985).

Crosson and Stout (1983) cite a study where large quantities of organic matter were returned to the soil. Soil aggregation was increased 30 percent and bulk density was reduced from 1.3 to 1.1. grams per cubic centimeter. This appears very impressive but Crosson and Stout caution that although non-humic material can be increased over relatively short periods of time by returning crop residue to the soil, including leguminous forage crops into rotation and manuring, these non-humic materials rapidly decompose. It is the accumulation of humic material which has a strong influence on soil structure. This process is very slow.

Fertilizer amendments can indirectly improve the soil structure by increasing the amount of crop residue produced. A positive feedback relationship may be established.

Another consideration when applying fertilizer as an amendment is the differential erosion that exists within a field. This 'scattering' of erosional areas within a field poses problems for the treatment of nutrient deficiencies with fertilizer application. A uniform application of fertilizer will not be appropriate for all field areas. Technological advances into variable rate applications may result in the development of an acceptable system to deal with such situations.

Various industrial wastes, such as sugar lime, a by-product of sugar refining, may be effective amendments to reduce soil erosion. Some are currently being tested. The amounts of these available and the cost of transporting them may limit their usefulness to very restricted areas. Other chemicals, such as polyvinyl alcohol, are also very effective soil structure stabilizing agents. At present, the cost of such chemicals prohibits their use beyond research scale (Groenevelt et al. 1987).

2.4.7 Acceptability of remedial measures

The acceptability of remedial measures which are proven effective, from a soil conservation perspective, cannot be assumed as given. Assessments regarding the adoption of conservation tillage systems often presume incorrectly, that the resource conservation benefits are clearly evident (Allmaras et al. 1985). Swanson et al. (1986) contend that farmers generally opt to maximize short-run profits at the expense of land resource protection. Farmers in Canada and the United States have, over the past two decades, been forced to increase their scale of operation. "During the 1960 and 1970's the scale of agriculture increased because of market pressures, technological growth and relatively low interest rates" (Swanson et al. 1986). Many farmers throughout North America accepted heavy debt load during this expansionary period. Subsequent economic recession in both countries has left many farmers in financial difficulty. Earlier in this report the concept of "planning horizons" was introduced as part of a discussion of tolerable rates of soil loss. Over the past decade the economics of farming have not been conducive to lengthy planning horizons and thus have not been conducive to adopting soil erosion control practices. The reason for this is because returns on investment in conservation are generally held to be unrealized in the short term (Swanson et al. 1986).

In Ontario, the economics of conservation technologies have been examined by Stonehouse et al. (1987a, 1987b). These researchers note that monocultural corn and corn - soybean rotations have been much more profitable than traditional forage-based rotations. This profitability was based, however, on the long-term maintenance of yield levels despite the effects of soil erosion. While this may be possible on selected locations, evidence presented earlier in this review revealed that future yield reductions may frequently be expected with continued erosion despite current yield maintenance. Stonehouse et al. (1987a, 1987b) examined anticipated levels of profit associated with various cropping and tillage scenarios. They also estimated attendant soil loss for each scenario using the Universal Soil Loss Equation. The farm-level economic picture was taken to include annual net returns (in 1987 dollars) plus the present value of the farm business net worth at the end of a four-year and twenty-year planning horizon. This study assumed a land base of 200 ha featuring medium textured soil and 7% slope. Stonehouse et al. (1987b) found that, in the short term, a crop sequence of corn-corn-soybeans-winter wheat yielded the highest return irrespective of tillage technique. Slightly higher net returns (1%)

were associated with the use of conventional tillage over
conservation tillage. This slight difference was found to be offset by a
20% reduction in soil loss with mulch tillage. Substantial soil erosion
benefits were associated with a combination of no-till and mulch tillage in
a corn-soybean rotation.   However, such a system was accompanied by a 10%
reduction in return and was therefore deemed unlikely to be adopted in a
short term planning horizon. Other scenarios revealed a wide ranging set of
costs and benefits using conventional tillage. The scenario which resulted
in the lowest amount of soil erosion was also the least profitable. This
would suggest that soil conserving measures are inherently expensive to
farmers. While the total adoption of the most soil saving farming system
may be cost prohibitive, this study suggested that significant soil
conservation is available at marginal cost through the adoption of
conservation tillage only (Swanson et al. 1986, Stonehouse et al. (1987b).
The results of this study are limited to the parameters selected; however,
it does provide an example of the type of economic analysis that is required
by farmers for decision - making.

In the United States, the economics of soil conservation has been
studied in Iowa. Pope et al. (1982)simulated 18 farms which as a group were
representative of 1) the range of erosiveness existing in the state 2) each
of the soil types in the state and 3) the major land resource areas in the
state. A large number of scenarios were constructed by selecting various
options within three categories; crop rotations, tillage system and
supporting practices. Linear programming models were used to assess
economic returns to land, labour and management on each scenario for each of
the representative farms. Data requirements of the linear programming
models are very large and this study should be consulted for information on
methodology and the individual co-efficients.

The model, when applied, examined economically optional levels of soil
loss from the perspective of the individual farmer. A range of cropping
systems that resulted in various levels of soil loss and net return was
presented. Although the results of this study cannot be fully recounted in
this review, it was shown that a reduction in soil loss from the 1985 rates
could be achieved without reducing associated net returns. It was also
concluded that cropping systems which yield higher current net returns at
the expense of eroded soil, may prove less profitable in subsequent years
than other soil conserving systems. The fundamental conclusion of this

study, vis-a-vis Ontario, was that economically tolerable amounts of soil loss decline rapidly as planning horizons extend.

Swanson et al. (1986) have examined how the individual characteristics of farmers contribute to the adoption of soil conservation practices. They have been placed in three broad categories; source of information, personal characteristics and farm structure factors. Source of information implies the power of innovation diffusion and suggests that technology transfer is a key element of adoption. Personal characteristics have been examined by mainly researchers in the United States (Pope et al. 1982, Swanson et al. 1986). They contend that age, sex, education etc. impact on adoption behavior with younger farmers generally more receptive to innovation. This notion is based on the study of learning theory and the adult learning process. Generalization is obviously involved in such statements (Pope et al. 1982).

Farm structure factors relate to economic or managerial "realities" that prevent farmers from behaving in ways that are consistent with their attitudes (Swanson et al. 1986). Farmers who accept the merit of conservation technology on environmental grounds may be prevented from adoption because of short run cost or managerial complexity. Additionally, farmers under heavy debt load may be unwilling to accept the perceived risks and uncertainties of new technology (Swanson et al. 1986, Pope et al. 1982).

Clearly, the matter of socio-economic barriers to the adoption of conservation technology is as complex as the technology itself. Much literature is available, particularly from the United States, which examines the many economic and sociological forces affecting the implementation of remedial measures to control soil erosion. These include demographics, land tenure, institutional arrangements and many others. While this topic is of obvious importance to the full consideration of soil erosion in Ontario, it is thought to be beyond the scope of this review.

3.0 REDUCING PHOSPHORUS INPUT TO SURFACE WATERS

Nonpoint sources of pollution in both the Canadian and American Great Lakes Basin have long been recognized as key contributors to the declining quality of surface waters in these regions (Wall et al. 1982, International Joint Commission 1983). Erosion in the rural landscape has been recognized as a major cause of pollution in the Great Lakes (Wall et al. 1982). While sediment alone does not pose a serious threat to water quality, sediment

particles carry various nutrients, heavy metals and pesticides which cause serious damage (Miller and Spires 1978). Among the most active contributors to increased rates of eutrophication is phosphorus (Wall et al. 1982, Miller et al. 1982). The reduction of phosphorus loadings to Lake Erie has been identified as one of the major objectives of the Soil and Water Environmental Enhancement Program. The phosphorus component of the SWEEP mandate calls for a reduction of phosphorus load from non-point agricultural cropland sources to Lake Erie by 200 tons per year by 1990.

The consequences of phosphorus loading to the Great Lakes include excessive algal growth causing the fouling of beaches, the clogging of water intake system and depletion of oxygen supply in deeper waters (Baker 1985). These have been well documented through the work of PLUARG (1978) and other agencies (Hore and McLean 1973) over the past fifteen years. The purpose of this section is to examine certain key issues relating to the movement of sediment and/or phosphorus, and the control of such movement, from farm field to stream. In-stream processes, although significant to final delivery, are considered to be less amenable to remedial measures and consequently are not included in this review.

In consideration of the agricultural sources of phosphorus and the problem of excessive stream P loading, it is necessary to examine the types of available P, its agricultural practice-related origins, the physical processes responsible for transport and delivery and the extent and distribution of the problem in Southern Ontario. Only through accounting for each of these elements of phosphorus loss from cropland can the identification of effective technologies and the proper spatial allocation of remedial measures occur.

The issue of phosphorus loss, like soil loss, is complicated by many physical and human variables and interdependencies. Among the most significant is the soil erosion process itself. During this review and discussion of phosphorus loading it is useful to identify linkages and commonalities with soil erosion. Awareness of such linkages facilitates the identification of areas where problem conditions co-exist, thus maximizing the environmental return to properly selected remedial measures. In addition to identifying opportunities to address both soil loss and phosphorus control objectives in concert, recognition of inter-relationships will also aid in the identification of measures which have potential to worsen one condition while treating the other. For example, the utilization

of no-till technology may reduce soil erosion but leave increased amounts of
phosphorus on the soil surface thus contributing to increased P yield. The
following sub-sections review what is now known about various aspects of
phosphorus loss and its control.

3.1 Measurement and Prediction

It is generally held that phosphorus loss occurs, at varying levels,
on agricultural land in Southern Ontario. In order to identify key
contributing areas and reduce loading from agricultural lands it is
necessary to examine both the magnitude of present P loss and the likelihood
of future P loss. Tools of measurement and prediction are required. As
with soil erosion, direct measurement facilitates accurate analysis of
problem conditions on site-specific levels. Predictive abilities contribute
to efficient broadscale analysis and are essential to the development and
implementation of non-point pollution control programs.

Stream phosphorus loads have been measured in Ontario. Sediment data
monitored at watershed outlets are useful for validating predictions of
phosphorus transport with sediment from cropland (Rosseau 1985).
Unfortunately, relatively few rivers draining into the Great Lakes have
stations where suspended load has been measured regularly (Dickinson and
Wall 1977). Best results are achieved through regular and event-oriented
monitoring of sediment-associated and dissolved P concentrations. Dickinson
(1972) and Dickinson and Pall (1982) have shown that P loading varies
temporally and is strongly related to major storm (i.e. runoff) events.
Dickinson and Wall (1977) estimate that 80% of suspended material in
Southern Ontario waterways is moved downstream in less than 10% of the time.
These findings have been generally supported by studies conducted in Ohio
and elsewhere. Sporadic monitoring, and monitoring patterns which may miss
key events, do not provide accurate measures of stream P loads.

Measured P loads at the outlet of several representative Southern
Ontario agricultural watersheds were used by Miller and Spires (1978) and
Miller et al. (1982) to develop regression equations which related stream P
loads to the following watershed characteristics: average % clay and sand in
surface soil; fertilizer P, manure P and total P added; % area in
hay-pasture, alfalfa, row-crop, corn, woodlot or unimproved land; rural
residences; and stream densities.

In this study, measured P load at the watershed outlet was used to develop predictive methods. Multiple regression analysis was applied to 11 agricultural watersheds and showed that two characteristics - % clay in surface soil and % area in rowcrop - were of primary importance in explaining the variability of total P loads, accounting for 85% of total P variability. Regression was also used to examine total dissolved P and watershed characteristics. In this analysis, % clay and total P added (fertilizer & manure) were found to be significant. Fertilizer and manure added was found to be the most significant in predicting dissolved P load. Predictions of stream P loads have also been produced through the estimation

of contributions from individual agricultural sources. These sources were 1) runoff from cropland 2) runoff from livestock operations 3) runoff from unimproved land and 4) erosion of farm streambanks (Miller and Spires 1978, Miller et al. 1982). Runoff from cropland was found to be the major source of phosphorus from agricultural activities in the study watersheds. Estimates ranged from 50% to 92% with an average of 70%. Averaged contributions from livestock, unimproved land and farm streambanks were 20%, 3% and 7% respectively. In recognition of the importance of cropland runoff, it has been selected by SWEEP as a key target for remedial measures. Cropland runoff will be discussed more fully later in this section.

Miller and Spires (1978) attempted to validate regression equations by extrapolating total P load estimations to two larger watersheds (Saugeen and Grand) for which stream P at the outlet had been measured. It was found that loads from agricultural activities, estimated by regression, compared quite favourably with measured load. Base on the successful validation of this predictive method, the unit area load of total phosphorus from agricultural land in the subwatersheds in the Ontario portion of the Lower Great Lakes Basin was estimated by regression. Total P loading from agricultural activities was estimated to be 3,000 tonnes yr^{-1} with approximately 50% of this total P found in tributaries to Lake Erie (Miller et al. 1982). Subsequent mapping of load estimates revealed that the major contributing areas in southwestern Ontario were the level clay soils of Lambton, Kent and Essex counties (Miller et al. 1982). Although researchers endorsed these regression equations as a means of estimating stream P loads from agriculture they note that their reliability would be significantly improved with long-term measured data.

In the United States, agricultural nonpoint-source pollution monitoring programs have fallen into two general categories (Baker 1985); edge-of-field studies and regional water quality studies. In field level studies American researchers have collected water samples from rainfall simulations, research plots and individual fields. Baker (1985) notes that resulting data have most often been interpreted in terms of field rather than stream damage, and further notes that existing water quality models cannot extrapolate edge of field data to descriptions of regional water quality (Baker 1985, International Joint Commission 1983). American researchers have utilized methods, similar to those used by Miller et al. (1982) in Ontario, to produce regional water quality estimates. Baker (1985) echoes the concern of Ontario researchers regarding the need for regular long-term monitoring data in the development of reliable estimates of stream P loads.

A study conducted between 1974 and 1982 in northwestern Ohio on level, fine to medium textured soils found large annual variations in sediment loading and thus large variations in P loading. Rural non-point sources accounted for 51% of total P (Baker 1985). This study also examined the effectiveness of measures such as conservation tillage for the control of phosphorus from cropland. These findings will be discussed later in this report.

Researchers in the Ohio study found unit area P loads were nearly three times the national average from agricultural land while gross erosion rates were less than the national average (Baker 1985). This situation was attributed to the proliferation of rowcropping on soils with relatively high clay content. Such a conclusion is consistent with the findings of Miller and Spires (1978) in southwestern Ontario reported earlier.

While the research described in the preceding paragraphs was based primarily on measurement and monitoring, several mathematical models have been developed for predicting nonpoint water pollution. Two types of mathematical models are discussed by De Coursey (1985): they are empirical and physical process models. While empirical models such as regression and statistical time series analysis are generally well understood and relatively simple to apply, DeCoursey observes that they are "difficult to improve, difficult to extend beyond the range of data used in their development, are easily misapplied and can be misleading about cause and effect" (De Coursey 1985).

Physical process models have been used to predict responses and assess effects of various environmental conditions (scenarios). Unfortunately, process models are generally thought to require very high data inputs to develop and extensive research to validate. Most relevant to our examination of stream P loading has been the development of several surface runoff models capable of simulating the movement of water and pollutants over and through the soil to stream channels.

The most notable of these are well summarized by De Coursey (1985) in the Journal of Soil and Water Conservation. The following brief description of these models is largely taken from this article. Specific references for each are provided for those wishing detailed information.

The Hydrologic Simulation Program Fortran model (Johanson et al. 1980) simulates the movement of dissolved oxygen, organic matter, temperature, pesticides, nutrients, salts, bacteria, pH, sediment and plankton from the land surface through stream systems. This model, while comprehensive, requires enormous quantities of data based on many years of record. Difficulties relating to the availability of such data in Canada have already been noted.

A less detailed runoff model has been developed at Purdue University in Indiana. The Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al. 1980) is a physically based model that can be used to study the effect of land management on soil erosion and sediment yield. ANSWERS has been used by Beasley et al. (1980) to assess the impacts of conservation tillage on the movement of sediment and phosphorus from the midwestern Lake Erie Basin (Ohio, Indiana, Michigan). The model was used with a P transport relationship for simulation purposes.

Only one model has been developed in the U.S which specifically simulates the response of field-sized areas. The Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel 1980) model consists of several options to simulate tillage, crop growth, erosion, sediment yield and plant nutrient movements. This model has been used extensively in the U.S. on field scale research and is presently being revised in order to expand its assessment capabilities. Several other models have been developed throughout the United States which examine erosion and associated sediment yield at varying levels. These are too numerous to include in this report.

Physical process models have been developed and successfully utilized in Ontario. The Guelph model for evaluating the effects of Agricultural

Management Systems on Erosion and Sedimentation (GAMES) has been developed
by Cook et al. (1985) at the University of Guelph. GAMES estimates seasonal
and spatial erosion losses and subsequent delivery of sediment at the outlet
of small agricultural watersheds. The model accommodates combinations of
spatial land units of any size and shape and is able to utilize seasonal
time frames to reflect changes in soil erodibility, cropping and climatic
conditions. The Universal Soil Loss Equation and a delivery ratio function
are used in GAMES to account for soil loss and delivery to stream (Dickinson
and Pall 1982).

The GAMES model has been used by Dickinson and Pall (1982) to examine
soil loss/delivery and to evaluate a variety of agricultural management
scenarios in several southwestern Ontario subwatersheds. Regarding erosion
and delivery they found that in an upland watershed, 62% of spring sediment
load originated from 15% of the watershed. Conversely, examination of a
lowland watershed revealed that sediment yield was much more uniform.
Proximity to stream was found to strongly influence sediment yield on both
sloping and level fallow land. On sloping land, primary reasons were high
rates of erosion. High delivery ratios accounted for increased yield on
level land. As distance from stream increased, steeply-sloped row-crop
areas were found to contribute little if any sediment regardless of in-field
erosion rates (Dickinson and Pall 1982). The findings of Dickinson and Pall
(1982) regarding potential impact of management practices are summarized
below:

- Soil erosion and sediment yield reductions did not necessarily occur in
  concert.

- Crop rotations and surface residue management were predicted to
  potentially reduce soil loss by 50% to 75%.

- Only minor reductions in sediment yield accompanied measures intended to
  reduce soil loss. Specific field level measures such as strip-cropping
  and buffer strip have been observed to produce significantly greater
  reductions in sediment yield than in soil loss.

Researchers concluded that it was necessary to differentiate between rolling
upland and level lowland watersheds when assessing soil erosion and sediment
yield. Upland watersheds were found to exhibit localized erosion which, if
controlled, would significantly reduce sediment loads. These areas of
erosion are most often situated in close proximity to surface water (natural
or drainage ditch). It should be noted that they may not necessarily

correspond with the areas of erosion resulting in crop yield reduction which were discussed earlier in this report. The existence of localized erosion suggests the possibility of identifying and focussing on key contributing areas in the delivery of remedial programs. In lowland watersheds, given the expansive nature of relatively low rates of erosion, it was not possible to identify discrete contributing areas; consequently the application of widespread control measures would be required in order to significantly reduce sediment/phosphorus yield. These findings are of key importance to the allocation of tolerable rates of P loss, discussed in the next section.

Recently, the GAMES model has been slightly modified to specifically account for phosphorus loss (Rousseau 1985). This revised version of GAMES estimates the total phosphorus concentration of surface soil, potential soil loss, field to stream sediment yield and field to stream phosphorus enrichment. This model has been utilized in a study of a subwatershed of the Avon River in Perth County (Rousseau 1985). Application of this model revealed that the spatial variability of P yield corresponded with the variability of sediment yield. In this study, conducted on rolling topography, most sediment and phosphorus loading was found to emanate from steeply sloped corn and grain fields located near drainage channels. These findings agree well with observations from upland applications of the original GAMES model noted earlier. Applications of the revised GAMES model for phosphorus are limited in number but appear to substantiate rather than refute the validity of existing process models.

3.2 Tolerable Phosphorus Loads

Over the past decade, both the scientific and political communities have debated tolerable phosphorus levels in the Great Lakes. Desired reduction levels for Lake Erie, the shallowest of the lakes, have been established and represent a key element of the SWEEP programs mandate. Given a specified tolerable phosphorus level at the lower limit of Erie Basin river systems, upstream locations must be examined to determine where, and in what manner, sufficient P loss reductions might be achieved.

Two options would appear to exist for the allocation of tolerable P levels across the southwestern Ontario landscape. These are 1) uniformly applied rates across all areas or 2) the identification of specific areas (i.e. targeting) for intensive treatments. The concept of uniform application of phosphorus reductions suggests an equitable spatial

distribution of available technical and financial assistance and also
implies that farm level costs associated with reducing P loads will be
evenly borne amongst southwestern Ontario farmers. Such an approach, while
appearing equitable on social and political grounds, is unlikely to provide
best results. As discussed earlier in this report, Miller et al. (1982) and
Dickinson and Pall (1982) have shown that P loading is not uniform across
the Southern Ontario landscape but varies both spatially and seasonally.

The identification and treatment of priority areas recognizes the
variability of sediment and phosphorus loss and attempts to achieve the
greatest improvements in water quality for the minimum regional investment
in revised management practices (Maas et al. 1985). The value of effective
targeting has been well established for both erosion control and phosphorus
load reductions in Canada and the United States (Lovejoy et al. 1986). A
study conducted in Indiana, in 1982, examined the cost effectiveness of
targeted and non-targeted erosion control programs (Lee et al. 1985). While
specific findings varied with the simulated rate of adoption, it was
demonstrated that in all cases, targeting increased cost effectiveness
substantially.

If the merits of targeting are established and accepted it is necessary
to consider the methods and options for selecting critical areas. The
diverse topography, soil types and current management practices occurring in
Southern Ontario suggest that the causes and processes of phosphorus loss
are not uniform on broadscale levels but rather that they vary between and
within regions.

Researchers in Canada and the United States have developed predictive
methods, based on physical process models such as GAMES, CREAMS, ANSWERS
etc., to construct and evaluate scenarios representing the various physical
and cultural factors which influence P loading. Such predictive methods
contribute to the assessment and comparison of a broad range of P allocation
alternatives. As noted earlier in this report, best alternatives or
scenarios will be those which maximize P reductions while minimizing cost
and complexity and which also contribute to the achievement of soil erosion
objectives. With reference to alternatives, it was noted in section 3.2
that upland watersheds are characterized by widely variable rates of P loss
with high proportions emanating from a relatively small percentage of the
landscape. Dickinson (unpublished data) has determined that up to 80% of P
loading is produced from 20% of the area in rolling upland watersheds in

southwestern Ontario. Selection of an upland scenario implies rigourous application of remedial measures to specific land units. Alternatively, Miller et al. (1982) have found that P loading from relatively level, fine textured soils, such as those found in Kent and Essex counties, is comparatively high. In contrast to upland areas researchers (unpublished data) observe that sediment and P transport is occurring over most of the landscape with excessive P loss attributable to the cumulative contribution of many land units. Selection of lowland targets thus implies the application of remedial measures over large areas.

Dickinson (unpublished data) notes that areas of excessive P loss in upland watersheds are usually associated with soil erosion. Such findings indicate the need to control soil loss in order to reduce P yield. Conversely, high P loadings in level lowland areas is largely attributable to very high delivery ratios and is not associated with excessive soil loss from the standpoint of productivity. These variations in causes of P loss represent important inputs to the development of representative scenarios for the evaluation of spatial alternatives in the allocation of phosphorus load reductions.

Finally, little information could be found in the literature regarding similar allocation strategies in the United States. However, several researchers do stress the importance of recognizing the significance of dissolved bio-available P and recommend that emphasis be placed on the treatment of this form of P above any other consideration (Baker 1985, Sonzogni et al. 1982).

3.3 Areal Extent

Research conducted on eleven agricultural watersheds in southwestern Ontario formed the basis for an extrapolation of stream P loads to the Southern Ontario portion of the Great Lakes Basin (Miller and Spires 1978, Miller et al. 1982). Methods were discussed in section 3.1. This research produced values for contributions of phosphorus from agricultural sources at a broadscale level. While such information represents a valuable estimation of the areal extent of P loading, the researchers note that its reliability would be significantly improved with long term data from monitoring. Although the absolute values produced by regression analysis are limited by data, the research noted above does provide a reasonably reliable ranking of contributing areas.

Research by Miller et al. (1982) Miller and Spires (1978) and Wall et al. (1982) has examined the magnitude of sediment and phosphorus loss, independent of any consideration of tolerable loading. The allocation of tolerable P discussed in section 3.2 will provide a useful basis for comparison with actual loading to identify areas of excessive P loss.

We suggest that the comparison of various allocation scenarios with estimated actual P loading will produce mappable illustrations of the areal extent of excessive stream P loading. Further comparison with regional soil loss mapping (Shelton et al. 1984) may reveal areas in which both SWEEP objectives might be addressed in concert.

3.4 Sources and Forms of Phosphorus

Phosphorus yield from agriculture has been studied with respect to the relative contributions of specific agricultural activities in southwestern Ontario. PLUARG researchers (Miller et al. 1982) have identified 4 major sources of phosphorus; 1) surface runoff from cropland 2) runoff from livestock operations 3) streambank erosion, and 4) runoff from unimproved land. Other sources were found to be significant in localized situations. These were drainage of organic soils, seepage from private septic systems and the addition of contaminants such as milkhouse wastes through illegal drain hookups.

In southwestern Ontario, cropland was found to be the most significant source of phosphorus accounting for an estimated 70% of stream loadings (Miller et al. 1982). Other sources were found to be less significant on average with livestock accounting for 20% of total P loading. The contribution from streambank erosion and unimproved agricultural land averaged 7% and 3% respectively. In recognition of the importance of cropland as a source of phosphorus, the SWEEP program has been designed to focus on this issue. Consequently, other sources will not receive further attention in this report.

Miller and Spires (1978) found that the proportions of particulate P to total P from cropland increased with increasing sediment concentration, and conversely that the proportion of dissolved reactive P to total P from cropland declined as sediment concentration increased. It was observed that dissolved P, the most bio-available form of phosphorus, was greatest from fields with fertilizer and/or manure on the surface. A model has been developed by PLUARG researchers which predicts sediment associated

phosphorus yield (Miller et al. 1982). This relationship has been expressed as "Sediment P in cropland runoff = soil loss x P content in surface soil x P enrichment ratio x sediment delivery ratio".

As noted earlier in this report, research in Ontario (Miller et al. 1982) and in the United States (Baker 1985) has shown that most of the P entering Lake Erie is in particulate form. A study conducted by Baker (1985) in the western Erie Basin of the United States, found that 80% of total P was in particulate form, 25% of which was bio-available. Conversely, of the remaining 20% in dissolved form, 90% was found to be bio-available. Such findings would appear to relate directly to the concept of tolerable loads and allocation alternatives discussed in section 3.2. Baker (1985) observed that the focussing of remedial measures on areas of high soil loss and sediment yield may reduce the quantity of relatively unavailable particulate P while increasing the quantity of highly bio-available dissolved P. The reasons for this will be clarified in a discussion of remedial measures presented later in this report.

Sonzogni et al. (1982) acknowledge that particulate P often represents a high proportion of the total P input to lakes and thus represents a major reservoir of P to organisms. Particulate P fractions can consist of organic, inorganic and condensed forms. The inorganic P fraction is the most significant as a source of bio-available P. Particulate inorganic P is further divided into nonapatite and apatite fractions. Researchers have observed that apatite P is only slightly soluble in most natural waters and thus largely unavailable for plant uptake (Miller et al. 1982, Sonzogni et al. 1982).

As noted earlier, dissolved reactive or dissolved inorganic P is the directly bio-available form of phosphorus (Sonzogni et al. 1982). Other forms are available only through conversion to inorganic phosphate. Other forms of P in solution include dissolved condensed phosphates and dissolved organic P. The potential for these other forms of dissolved P to be converted to bio-available forms is significantly affected by characteristics of the receiving water and the source from which the P was yielded. Sonzogni et al. (1982) have noted that waste water more rapidly converts non-available P to available forms. Similarly, they observed that dissolved organic P released from plant tissue and animal waste is converted rapidly to dissolved reactive P when released into streams, while that from soils is more stable and less susceptible to conversion.

3.5 Processes and Causes of P Yield in Cropland Runoff

Similar to the earlier discussion of the processes and causes of soil erosion, it is necessary to examine and understand these elements of the phosphorus loading problem. Knowledge of the processes and causes of P yield will form a basic input to the selection/development of effective remedial measures.

It is clear that particulate-P loading is governed by those processes affecting soil erosion. While the processes of detachment and transport are fairly well understood, stream P loading also requires the delivery of eroded sediment.

It is generally agreed that the concept of delivery ratio is critical to the identification of areas which are actually yielding excessive P to streams. Researchers note that movement within a field does not necessarily equal delivery (Dickinson and Pall 1982).

In Ontario, estimations of sediment loads have combined the Universal Soil Loss Equation and a specified delivery ratio. The USLE, its applications and limitations were discussed earlier in this report. Miller et al. (1982) and Wall et al. (1982) have used delivery ratio values provided by the Soil Conservation Service (1973) in the United States to produce estimates of P loading and sedimentation respectively. Researchers in Ontario and elsewhere have also attempted to utilize physical process models to better calculate delivery ratio (Dickinson and Pall 1982, Rousseau 1985). Models such as GAMES, CREAMS and ANSWERS offer potential to accurately determine field level delivery ratios by including specific information for location, topography, cropping and management etc. A search of relevant literature, however, suggests that little validation of these models has occurred at field level vis-a-vis the determination of delivery ratios. With reference to the validation of delivery ratios, the importance of re-examining the relationship between sediment source (erosion) and delivery must be emphasized. In the past, the final product, sediment load, has been measured and the source (erosion) estimated with the Universal Soil Loss Equation. These values have then been used to calculate a delivery ratio value. However, discussion of the USLE earlier in this report suggested that the validity of the predictive ability of the USLE in Ontario is, at best, questionable. Review of sediment source in the sedimentation equation inherently implies re-evaluation of delivery ratio as well.

Unlike sediment-associated P, dissolved P is transported via runoff and is independent of the soil erosion process, requiring only the delivery of water to the stream in order to contribute to loading. As discussed earlier in this section, dissolved reactive phosphorus is the most readily available for uptake by plants.

PLUARG researchers (Miller et al. 1982, Miller and Spires 1978) found that dissolved reactive P in eleven agricultural watersheds in southwestern Ontario, was greater from fields possessing high available P levels and in areas with manure on the soil surface. Dissolved reactive P in 10 samples of runoff from fields to which manure had been applied but not incorporated averaged 0.69 mg L^{-1}. Samples from 33 fields which contained no manure or in which manure had been incorporated averaged 0.098 mg L^{-1}. In addition to dissolved reactive P from manure and fertilizer added, Sonzogni et al. (1982) indicated that dead or dying vegetation may release significant quantities of bio-available phosphorus. Consequently, researchers have noted that dissolved P may also be relatively high in runoff from fields in perennial forage due to P released from dead vegetation.

Finally, as noted earlier, PLUARG researchers (Miller et al. 1982) and American scientists (Baker 1985) have observed that dissolved P represents a relatively small proportion of total P from agriculture under present management systems. However, the high bio-availability of this form of P makes it significantly more damaging per unit P than associated particulate forms. While much research has centred on the perceived need to control particulate P, we caution that land and program managers must not adopt measures which will inadvertently increase the yield of highly bio-available dissolved reactive P.

3.6 Remedial Measures

Remedial measures to reduce phosphorus loading from cropland sources must recognize the basic elements of P yield which were identified in section 3.5. These are P content at the soil surface, soil loss, delivery ratio and P enrichment ratio (Miller et al. 1982). In order to reduce P loads, remedial measures must reduce one or more of these components without increasing other components proportionately. The following discussion addresses remedial measures as they relate to each of these key components of sediment associated P. As noted earlier sediment associated P has been

found to be the dominant form of phosphorus entering Lake Erie (Miller et al. 1982).

3.6.1 Soil loss

Available measures to control soil loss have been discussed in section 2.4. It was found that the two most promising general measures were cropping systems and conservation tillage. Researchers in Canada and the United States have examined the role of conservation tillage in preventing soil loss and associated P loading. Baker and Laflen (1983) state that the reduction in soil erosion possible with conservation tillage compared with conventional tillage is valuable from a water quality perspective based on associated reductions in sediment and nutrient losses. These researchers also contend that, in some cases, runoff can be lessened with conservation tillage thus reducing losses of soluble, non-adsorbed P. In other cases, however,the maintenance of crop residue on the soil surface limits fertilizer use options and may result in increased P concentrations which would negate the water quality benefit of reduced runoff (Baker and Laflen 1983). This will be discussed in section 3.6.3.

Romkens et al. (1973) observed that total P losses have been found to decrease, due to soil loss reductions, with conservation tillage systems. However, studies have also indicated that concentrations of dissolved P may substantially increase with conservation tillage (Andraski et al. 1985, Romkens et al. 1973). The implications of this relationship were discussed in section 3.5. Researchers have also found that, in some instances, available sediment P concentrations and losses have been greater for conservation tillage relative to conventional tillage (Andraski et al. 1985). The reasons given for this were the existence of unincorporated manure and a release of P from crop residues. While increases in P concentration of surface soil have been traced to conservation tillage, it is generally agreed that, in most cases, reduced soil loss will result in reduced total P but that the measurable reductions in P will not be as great as the reduction in soil erosion.

Andraski et al. (1985) have studied total P reductions associated with conservation tillage in the United States. In this study, fertilizer was subsurface banded at planting thus reducing the offsetting impacts of increased surface P concentration. With the elimination of the surface fertilizer factor it was found that no-till, chisel-till, and till-plant treatments on corn reduced total P losses by an average of 81, 70 and 59%

respectively relative to conventional moldboard tillage. Even more
significant was a reduction of bio-available P over the study period (4
yrs) with no-till, chisel till and till plant by 63, 58 and 27% respectively
(Andraski et al. 1985). These findings, as well as those of Mueller et al.
(1984) substantiate the value of conservation tillage for the reduction of P
loading when surface fertilizer is controlled. Non-incorporation of
fertilizer has been observed to produce nearly inverse results.

3.6.2 Phosphorus enrichment ratio

Phosphorus enrichment ratios (PER) have been calculated as the ratio of
the P content of sediment (eroded soil) to that of the source soil. The
phosphorus enrichment ratio depends primarily on the surface soil texture
and the rate of soil loss. As noted earlier in this report, P is adsorbed
most readily by the fines i.e. clay particles. As these fractions are also
the most easily eroded, source areas exhibiting high clay content will
display a high phosphorus enrichment ratio.

With regard to the relationship between erosion and enrichment, Massey
and Jackson (1952) observed a reduction in the enrichment ratio as storm
sediment concentrations and soil losses increased. Massey and Jackson
(1952) used regression equations to estimate the effect of available P,
surface runoff and soil loss on a phosphorus enrichment ratio. They found
that PER increased as soil loss decreased and thus concluded that a practice
which reduced sediment loss will not reduce nutrient losses proportionately.
No measures are available to offset this relationship between soil loss and
PER but, as noted earlier, reduction in soil loss is usually greater than
the increase in the phosphorus enrichment ratio; thus a net reduction in
total P loading will occur.

3.6.3 Phosphorus concentration in surface soil

Adequate phosphorus fertility is essential for economically viable crop
production. In recognition of the value of adequate P levels, most
landowners in Southern Ontario apply fertilizer phosphorus to cropland as a
routine part of their management system. PLUARG researchers (Miller and
Spires 1978) have compared the average fertilizer P used on crops grown in
several Southern Ontario watersheds to the average amount required for most
economic production. It was found that, on average, fertilizer P additions
exceeded the estimated requirements for all crops except hay-pasture. The

application of excessive fertilizer P was predicted to increase the level of available P in the soil and the amount of P in runoff from fertilized fields (Miller and Spires 1978). Researchers further observed that the dissolved P concentration in runoff was increased to a greater extent than total P due to the solubility of recently applied fertilizer.

As noted in section 3.6.1., non-incorporation of fertilizer P or manure in a conservation tillage system may directly contribute to increased P yield from cropland. Baker and Laflen (1983) observed that the amount of nutrient in the soil profile directly influences the concentrations of nutrient in sediment and water. The amount present in the profile has been described as the sum of the amounts naturally present, the amount carried over from previous applications and the amount being added (Baker and Laflen 1983).

In addition to the amount of P present, its position in the soil profile strongly affects its concentration in runoff. As stated earlier, many researchers have noted a relationship between conservation tillage systems and the concentration of phosphorus at or near the soil surface. Alberts and Spomer (1985) and many others have discussed the stratification of nutrients in the soil profile under conservation tillage (no-till) systems. Unlike the moldboard plow which mixes nutrients and other chemicals throughout the plow layer, a no-till system accomplishes little if any vertical distribution of P through the soil profile.

In addition to fertilizer P, excessive phosphorus concentrations can be attributable to high rates of manure application. Like fertilizer, manure P can become serious when combined with no-till, or reduced tillage system. As reported earlier, Miller et al. (1982) found that dissolved P was high from fields having high available P or manure on the surface. These findings were provided in section 3.5. While the issue of manure-associated P in a conservation tillage system appears significant, a review of the literature did not produce any additional information regarding effective methods of manure management.

In the case of both fertilizer and manure P, land managers face difficult issues. Management based solely on water quality objectives suggests that nutrients should be incorporated into the soil to reduce chemical loss. However, in order to provide protection against erosion, many farmers are now seeking to maximize crop residue on the soil surface. Incorporation is not particularly acceptable from the standpoint of surface

protection. Technologies such as shallow tillage or the use of "knives" to apply manure are being studied but Baker and Laflen (1983) suggest that their potential is limited. Soybean residue for example, is reduced by 61% with a single disking. Research is being conducted in the United States on the development of a "point injector applicator" that incorporates liquid manure without residue incorporation. Further research is reported on an implement designed to incorporate both nutrients and pesticides without incorporation of residue (Baker and Laflen 1983). Unfortunately, little published information is presently available on this research.

3.6.4 Sediment Delivery Ratio

The sediment delivery ratio is the major factor which, in conjunction with soil loss, determines P load. As indicated in section 3.5, the sediment delivery ratio is dependent on soil texture and topographic features. The proportion of the eroded soil that reaches surface water is greater in fine textured soils. Delivery is reduced by topographic features that reduce the rate of water flow or increase the time required for runoff to reach surface water courses. Dickinson and Pall (1982) and Rousseau (1985) note that distance from soil source to water course is a major determinant of delivery.

Dickinson and Pall (1982) and Baker and Laflen (1983) suggest that on medium textured rolling topography, increased surface roughness and infiltration caused through disruption of the soil surface by tillage and/or surface structure improvement will reduce delivery ratio. A search of the literature did not produce any research findings which document the extent of this reduction.

Buffer strips or other riparian vegetation that slows the movement of water have also been observed to be effective in reducing sediment and P delivery. Dickinson and Pall (1982) applied GAMES in a predictive mode and determined that such measures are effective in reducing sediment load on level areas. Unfortunately, P load can not be expected to decline by the same amount because of the influence of the phosphorus enrichment ratio, discussed earlier in this report.

With regard to P loading from cropland sources, PLUARG researchers (Miller et al. 1982, Wall et al. 1982) estimated that the areas of highest yield in southwestern Ontario are the level, fine textured soils of Kent, Essex and Lambton counties. Fine textured clay soils have been found to

remain in suspension for long periods of time. Ontario researchers (Dickinson and Pall 1982, Rousseau 1985) have thus observed that total volume of runoff rather than velocity are critical to P loading on level fine textured soils. Buffer strips along water courses have been suggested as possible remedial measures for the reduction of P loading from lowland areas. It has been shown, however, that sedimentation is seasonably variable with highest rates occurring during early spring (Dickinson and Pall 1982). During this period of the year there is no growth on the buffer strip and its effectiveness is therefore greatly reduced. In view of the foregoing, measures to reduce soil detachment and to improve subsurface drainage and infiltration would be more effective in reducing P load from these areas.

Methods for reducing soil detachment include improved structural stability through cover cropping and tillage. Each of these measures was discussed in section 2.4. Unfortunately, in southwestern Ontario, these measures are not easily applied to fine textured, level soils. The predominance of row cropping does not encourage the utilization of soil structure building crops, other than the combination of winter wheat and underseeded red clover. Difficulties relating to forages, particularly the lack of an off-farm market were also discussed in section 2.4. Little information is available in the literature regarding the effects of different perennial forages on the structure of fine textured soils. Most research, as reported earlier, has focussed on yield-related implications of various tillage and cropping methods for fine textured soils.

Subsurface drainage is an accepted practice on nearly level fine textured soils. Where soils are naturally poor in drainage, tile draining increases the volume of water flowing into the soil (infiltration) and therefore reduces the volume of water flowing over the surface of the soil (runoff). In areas where the volume of surface runoff is a major problem, tile drainage could have significant impact in reducing that volume. On these areas, the objective of farmers is to remove the surface water quickly; hence surface drains are used extensively.

For tile drainage to be effective, the water must be able to flow into the tile drain at a reasonable rate. The rate of conductance of the water flow through the soil depends to a large extent on soil structure and occurrence of large connected pores. Thus management can influence the efficiency of tile systems by influencing surface and subsurface soil

structure. Subsurface structure problems can possibly be by-passed in
relatively level topography by using smaller diameter, near-surface tile
systems. Near-surface tile systems have not been adequately field tested.
In soils with rolling topography, where the velocity of surface water flow
is a major cause of soil erosion, the significance of tile drainage as a
remedial measure will be greatly reduced.

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